NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

THE ANALYSIS OF COMPONENTS, DESIGNS, AND OPERATION FOR ELECTRIC PROPULSION AND INTERGRATED ELECTRICAL SYSTEM

by

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September 1998

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY ***(Leave blank)***

2. REPORT DATE
September 1998

3. REPORT TYPE AND DATES COVERED
Master's Thesis

4. TITLE AND SUBTITLE
THE ANALYSIS OF COMPONENTS, DESIGNS, AND OPERATION FOR ELECTRIC PROPULSION AND INTEGRATED ELECTRICAL SYSTEM

5. FUNDING NUMBERS

6. AUTHOR(S)
Arrington, Jess W.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey, CA 93943-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(maximum 200 words)*

The surface combatant of the 21st century will be designed to support a myriad of tasks requiring greater flexibility and endurance while keeping construction, maintenance and operating costs to a minimum. As a result the design of a surface combatant will depart from today's standards and philosophies. One option is the use of an electric propulsion system that can be integrated with the other ship's electrical loads. Electric propulsion operating with an Integrated Electrical System has many advantages that will fulfill the requirements of future surface combatants.

This study provides the historical background, the supporting issues, components, and architecture of electric propulsion systems and the Integrated Electrical System. Technical information on various component types and issues that influence the design considerations of an electric propulsion system and Integrated Electrical System to meet the requirements of a surface combatant are addressed. The areas of study are prime movers, generators, frequency converters, motors, ship's service electrical distribution, auxiliary electrical loads, and system control.

The designer and operator of the surface combatant of the 21st Century can better understand the application of an electric propulsion system and Integrated Electrical System from the accrued information on components, system architecture and system control herein.

14. SUBJECT TERMS Electric Propulsion, Ship's Propulsion, Prime Movers, Generators, Synchroconverter, Cycloconverter, Pulse Width Modulation, Synchronous Motors, Synchronous Machine Ship's Service Electrical System, Integrated Electrical System, Ship's Service Distribution System, Ship's Service Electric Generator, six-pulse, 12- pulse, DC ZEDS, Electro-magnetic Aircraft Launching System, Pulse Energy Weapons, Power Electronic Devices.

15. NUMBER OF PAGES
136

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFI- CATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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THE ANALYSIS OF COMPONENTS, DESIGNS AND OPERATION FOR ELECTRIC PROPULSION AND INTEGRATED ELECTRICAL SYSTEM

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
September 1998

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ABSTRACT

The surface combatant of the 21^{st} century will be designed to support a myriad of tasks requiring greater flexibility and endurance while keeping construction, maintenance and operating costs to a minimum. As a result the design of a surface combatant will depart from today's standards and philosophies. One option is the use of an electric propulsion system that can be integrated with the other ship's electrical loads. Electric propulsion operating with an Integrated Electrical System has many advantages that will fulfill the requirements of future surface combatants.

This study provides the historical background, the supporting issues, components, and architecture of electric propulsion systems and the Integrated Electrical System. Technical information on various component types and issues that influence the design considerations of an electric propulsion system and Integrated Electrical System to meet the requirements of a surface combatant are addressed. The areas of study are prime movers, generators, frequency converters, motors, ship's service electrical distribution, auxiliary electrical loads, and system control.

The designer and operator of the surface combatant of the 21^{st} Century can better understand the application of an electric propulsion system and an Integrated Electrical System from the accrued information on components, system architecture and system control herein.

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I. INTRODUCTION

Marine engineering systems are currently undergoing another period of revolution brought about by advances in power electronics and machine technology. The intent of these developments is to maximize a ship's capabilities while reducing manning requirements and entire life cycle costs. New generations of electric propulsion and Integrated Electric System (IES) technology have been established as strong contenders for future surface combatants. There are numerous advantages associated with electric propulsion and IES that justify their potential use. This thesis seeks to explore the various components and system designs and to provide comprehensive details into the operation and control of a suitable electric propulsion system and an IES.

The objectives of this thesis are to provide an overview of current technology and architecture relevant to electric propulsion, compile a detailed list of systems that would comprise an IES, and outline the operation of both the electric propulsion system and the IES to provide information to designers and operators of the next generation of marine engineering systems. A special emphasis is placed on identifying the types, operation, advantages, disadvantages and control of frequency converters, six-phase propulsion motors, auxiliary loads and propellers for the proposed electrical propulsion system and IES.

A. HISTORY OF ELECTRIC PROPULSION

1. History of Ship's Using Electric Propulsion

The propulsion of ships and submarines with electric motors is not a recent innovation. The first recorded use of marine electric propulsion was in the 19^{th} century when a small battery-powered, electric-propelled passenger launch was built and operated in Russia [1]. Interest was renewed in electric propulsion at the turn of the 20^{th} century when the development of steam turbines for main propulsion required a speed reduction from the prime mover to the propeller shaft. In 1908 a system consisting of a turbine-driven generator and two propulsion motors was installed on a German vessel and a similar system was installed on a fireboat in the U.S. [1]. Between 1911 and 1913 the U.S. Navy installed a 5,500 Horsepower (HP) wound rotor induction motor in the collier *Jupiter*. This ship later became the U.S. Navy's first aircraft carrier *Langley*. The vessel operated for 31 years and was lost in combat action in

1943. In the past 87 years there have been numerous individual ships and entire classes of ships that have used electric motors for propulsion. In the period between World War I and World War II, the U.S. Navy built 50 vessels which used electric propulsion. These vessels included the aircraft carriers *Langely* and *Saratoga* and the battleships *New Mexico, California, Maryland, and West Virginia* [2]. Submarines also benefited from the use of electric propulsion for operations underwater. Installations in the early era of turbine-driven generators operating in electric propulsion plants approached 150MW (200,000HP) [1].

Electric propulsion was used extensively during World War II due to the lack of gear cutting capacity in the U.S. During World War II over 160 escorts ships and, most notably, 500 T2-Class merchant tankers were built that used electric propulsion [1,2]. By 1944 there were over 870 turbine-electric and 940 diesel-electric propulsion plants with a total of 10 million HP built or under contract in the U.S. [1]. After World War II, improved gear production and the increased space required for electric propulsion reduced their operation to specific niches where the characteristics were deemed beneficial.

In the 1980's and 1990's with advances in power electronics, manufacturing techniques, and materials for electro-magnetic machines, several new classes of ships have been built with electric propulsion systems. These new classes of ships include icebreakers, research vessels, ocean survey ships, oil tankers and numerous passenger liners [1].

2. Evolution of Designs for Electric Propulsion

Over the years electric drives have been of various designs with many different reasons for their applications. Electric propulsion was originally conceived to increase efficiency, provide redundancy and allow a variety of equipment layouts compared to direct propulsion systems. The first-large scale electric propulsion systems designed between 1900 and 1910 were diesel or steam prime movers powering DC generators which, in turn powered DC motors. The DC electric propulsion systems were primarily used on ships requiring 5,000HP or less. Due to the large amount of maintenance and the limited power of DC motors, their application in large ships were abandoned. The DC motors required contacts between the power supply and the windings on the rotor. The contacts required periodic maintenance and replacement as the motor operated. The DC motor also had to have contacts large enough to provide the power to the

rotor windings. These contacts limited the power that could be supplied to the rotor and in turn the motor output.

The first aircraft carriers and battleships designed with electric propulsion used steam turbines to drive AC generators, often referred to as turbo-generators, that provided power to AC motors. The output horsepower of the AC electric propulsion systems ranged from 5,000HP to 50,000HP [1]. These ships represented initial investigation of electric driven ships and their feasibility for separating equipment location and achieving redundancy. The majority of electric propulsion systems developed and used during World War II on surface ships used either steam turbines or diesel engines to run AC generators that provided power to synchronous AC motors to provide power levels between 5,000HP and 10,000HP. Also, the use of DC electric propulsion continued to be used in submarines and small auxiliary ships like ocean-going tugs and mine sweeps.

Speed control in these early AC electric propulsion systems was accomplished by changing the speed of the steam turbine or diesel engine resulting in a change in the generator output frequency. The generator output frequency dictates the speed of the synchronous AC motor. When the system was designed, the generator and motor had a specific number of poles with the generator having significantly fewer number than the motor. The following equation relates the frequency, speed and number of poles for a generator and synchronous motor [3].

$$f = \frac{n * N}{120} \qquad \text{Eq 1-1}$$

f = Electrical frequency of the AC voltage

n = Revolutions per minute of the generator rotor

N = The number of poles on the generator rotor.

When relating the speed of the generator to the speed of the motor, the electrical frequency from the generator equals the electrical frequency to the motor. The following equation relates the Rpm's of a generator to the Rpm's of the motor [3].

$$\frac{n_{Gen} * N_{Gen}}{120} = \frac{n_{Mot} * N_{Mot}}{120} \quad \text{Eq 1-2}$$

n_{Gen} = Revolutions per minute of the generator rotor

N_{Gen} = The number of poles on the generator rotor

n_{Mot} = Revolutions per minute of the motor rotor

N_{Mot} = The number of poles on the motor Rotor.

How these equations will illustrate the speed reduction and impact design issues for the generator and motor is discussed in a subsequent chapter of this thesis.

In the period after World War II very little research or development was done in the field of electric propulsion for ships. It was not until the early 1970's that electric propulsion was again revisited for use on surface ships. One of the most modern designs for an electric propulsion system is the *Queen Elizabeth II*, QE II. The QE II was overhauled in the late 1980's and outfitted with diesel-electric propulsion in place of the original steam plant. The QE II uses several diesel-driven AC generators that feed DC Link Converter units that provide variable frequency power to synchronous AC motors. The original steam plant for the *QE II* employing turbines employed and was costing enormous amounts of money in fuel and maintenance. By converting to diesel electric the owners of the QE II saved 30% in annual maintenance and fuel costs [4]. The ship needed to be fuel efficient but required a engineering plant that was reliable and quiet for passenger service. The decision was made to use numerous small, quiet diesel engines to drive AC generators to provide power to large synchronous AC motors. This design ensured a redundant engineering plant, providing safety and efficiency. The redundancy was achieved by having any of the diesel-driven AC generators provide power to any of the propulsion motors. Another savings was the use of the diesel AC generators for both propulsion and to supply the ship's service electrical load requirements. In the early 1990's numerous passenger ships have been built with electric propulsion including the *Fanasty Class* passenger cruise liners.

3. Renewed Interest in Electric Propulsion

Modern technology has given rise to a continued interest in electric drives [2]. New technology has been able to reduce the effect of electric propulsion's early shortfalls. These shortfalls included increased volumes for electric components, inefficient conversion of power from mechanical to electric and electric to mechanical and high maintenance requirements. Improvements have followed from advances in the field of power electronics that are making power transfer more efficient and compact. New technology in the field of manufacturing processes and the types of materials available in the construction of generators and motors have also given rise to smaller and lighter weight components. New designs for electric propulsion are being developed for the same reasons as its original conception and to support modern ship's service loads. In recent years there has been renewed interest in electric drives for ships propulsion in both civilian and military ships. Civilian ships use electric propulsion system to provide an increased availability of power for auxiliary equipment by using the propulsion generators in port instead of using large, more expensive ship service generators for power or providing dedicated prime movers to the auxiliary equipment . Types of auxiliaries powered by electric power from the ship's electric propulsion system are maneuvering thrusters, cargo pumps and cargo cranes to name a few. For the military, the reasons are far more complex and varied. Warships directly benefit from electric propulsion systems in terms of reliability, efficiency, flexibility and equipment layout and the ability to power auxiliaries. With current direct drives only the prime movers that are physically attached to a particular shaft can provide power to that shaft. With electric propulsion any prime mover and generator can provide power to any or all shafts. The use of electric drives allows prime movers and generators to be operated at the most efficient speed increasing the overall fuel economy of the ship. Also, with electric propulsion prime movers and generators will have a higher loading to support the entire ship load including propulsion and ship service requirements reducing the number of prime movers and generators online. This saves maintenance time and fuel for the ship. Cross connecting the system and multiple connecting points add flexibility and redundancy in the event of battle damage. Added flexibility in equipment and space arrangements are also made available with the use of electric propulsion.

B. THESIS CHAPTER OVERVIEW

This section contains an outline of the topical coverage of each chapter. The fundamentals of electric propulsion, including various components, operation and designs, and concepts that will be used throughout the thesis are introduced in Chapter II. Chapter III contains a presentation of the advantages and disadvantages of electric propulsion and an Integrated Electrical System (IES) and concludes with a discussion of why the US Navy is interested in using electric propulsion and an IES. The requirements for a proposed electric propulsion system and an IES are defined in Chapter IV. Chapter IV also contains an introduction to the different types of components available for use with electric propulsion and an IES. In Chapter V and VI the components, operating specifics, layout, operation and systems operation are analyzed. Chapter V concentrates on the electric propulsion. Chapter VI contains an analysis of the other subsystems of an IES and a detailed review of the various components and sub-systems.

A discussion is presented in Chapter VII on maneuvering controls of a ship utilizing electric propulsion and issues regarding operation and control for the IES. A description of a control architecture for a converter and synchronous motor is introduced and analyzed in Chapter VIII. Chapter IX contains the equations to model a six-phase synchronous motor. A proposed electric propulsion system and an IES are documented in Chapter X. Chapter XI contains conclusions to be drawn from this thesis concerning components, electric propulsion and IES designs and points of concern. Chapter XI will conclude with areas that require future research and development to optimize the effective employment of electric propulsion and an IES.

II. ELECTRIC PROPULSION BASICS AND INTEGRATED ELECTRICAL SYSTEM

This section contains an introduction to the fundamentals of past and present electric propulsion systems. All electric propulsion systems have three components in common: a prime mover, generator and motor. Even though the basic components are the same the method of operation and the design of these components may be totally different. The basic operating principles for electric propulsion are that a prime mover turns a generator which in turn provides power for an electric motor. Ship's speed is controlled by altering the electrical frequency and voltage applied to the motor for an AC system and altering the voltage level being applied to the motor for a DC system. The propeller thrust is controlled by changing the rotation of the motor or reversing the pitch of the propeller.

A. VARIOUS DESIGNS OF ELECTRIC PROPULSION

1. Alternatives in Designs for Electric Propulsion

There have been numerous designs for electric propulsion; but the three common components and the concept of operation have remained the same. There are four categories for variations in the design of electric propulsion. The type of power (AC or DC) to be used between the generator and motor, the method of speed control (change the voltage for DC or change the frequency and voltage for AC), method used to control the direction of thrust for the propeller (reverse the shaft rotation or reverse the pitch of the propeller) and the type of prime mover to be employed.

2. Principles of DC Electrical Propulsion

The earliest electric propulsion design used DC power. These DC units had limited power output, were large in size and maintenance intensive. DC electric propulsion systems continue to be used to deliver up to 5,000HP. This includes applications on surface combatants, submarines and auxiliary ships [2]. The type of prime movers for early DC electric propulsion systems were primarily diesel engines; however, early development of electric propulsion also used steam turbines. Diesel engines are still the principle prime movers used with DC electric propulsion. Speed control is accomplished by

increasing or decreasing the voltage to the motor. By increasing the voltage, the motor speed increases. The direction of rotation can be changed by changing the polarity of the motor voltage. DC electric propulsion systems are still used today in specific needs due to their advantages in speed control. Modern DC electric propulsion systems use efficient and compact AC generators which in turn feed electronic rectifiers. The rectifiers converts the AC power to variable voltage DC power to feed the propulsion motor. Modern technology has also increased the efficiency of the DC motor, but not to the point where current designs of DC motors will replace AC motors. The modern DC electrical propulsion systems are still limited to 10MW at 200rpm because of the maximum power that can be drawn through the commutator and

brushes [1]. The direction of propeller thrust in early electric propulsion systems was controlled by manually switching the polarity of the voltage being supplied to the motor. In modern electric propulsion systems, rectifiers are electronically controlled to change the polarity.

3. Principles of AC Electrical Propulsion

During the 1920's the next generation of electric propulsion was developed using AC power. The early AC electric propulsion systems used steam turbines as prime movers. Most AC electric propulsion systems used multi-phase generators to power multi-phase synchronous motors. The synchronous motor required both an AC voltage to the stator and a DC voltage to the rotor. The DC voltage allows magnetic coupling of the rotor to the stator magnetic field. With the first designs for AC electric propulsion systems, speed was controlled by changing the output frequency of the generator. The frequency change was accomplished by changing the prime mover's speed. As the prime mover turned faster the generator's output electrical frequency increased. With the increase in frequency, the propulsion motor increased in speed. A synchronous motor was used due to its characteristic of having no slip over given load changes. Simply stated, the motor turned at a set speed based on input frequency. Also, the system has an inherent correlation between generator rotor speed and motor rotor speed. By putting more poles in the motor than the generator, the motor will turn slower. The ratio of the number of poles in the generator to the motor is the inverse of the ratio of the corresponding speeds. This allows the prime

mover to turn at a high speed while the motor turns at a considerably slower speed. This is called electrical speed reduction. The majority of electrical propulsion systems still use synchronous motors. By using Equation 1-1 with a fixed number of poles for the generator and motor, a comparison can be developed relating generator speed to motor speed. The following table lists the electrical frequencies achieved by spinning a two-pole generator at a number of speeds.

Generator Rpm's	Electrical Frequency	Generator Rpm's	Electrical Frequency
1,800	30.00	2,700	45.00
1,900	31.67	2,800	46.67
2,000	33.33	2,900	48.33
2,100	35.00	3,000	50.00
2,200	36.67	3,100	51.67
2,300	38.33	3,200	53.33
2,400	40.00	3,300	55.00
2,500	41.67	3,400	56.667
2,600	43.33	3,500	58.33

Table 2-1. Electrical frequency for a two-pole generator.

Table 2-2 represents the corresponding rpm for an 80-pole motor being supplied the frequencies listed in Table 2-1.

Generator Rpm's	Electrical Frequency	Motor Rpm's	Generator Rpm's	Electrical Frequency	Motor Rpm's
1,800	30.00	45.0	2,700	45.00	67.5
1,900	31.67	47.5	2,800	46.67	70.0
2,000	33.33	50.0	2,900	48.33	72.5
2,100	35.00	52.5	3,000	50.00	75
2,200	36.67	55.0	3,100	51.67	77.5
2,300	38.33	57.5	3,200	53.33	80
2,400	40.00	60.0	3,300	55.00	82.5
2,500	41.67	62.5	3,400	56.667	85
2,600	43.33	65.0	3,500	58.33	87.5

Table 2-2. Comparison between rpm of 2-pole generator and 80-pole synchronous motor .

Today large electrical propulsion systems still use the basic AC design with certain changes based on modern technology. The first change is that the motor used may be of a different type. Two of the possibilities for replacing the wound-rotor synchronous motor are the permanent magnet motor or the induction motor. The permanent magnet motor has the same characteristics as the synchronous motor but does not require rotor excitation. The second change involves speed control via frequency converters rather than prime mover shaft speed. In both early and present day, reversing propeller thrust can be accomplished by switching two of the three leads to the AC motor causing the motor to rotate in the opposite direction. Two additional methods for reversing propeller thrust can be realized today: changing the phase sequence of the power converter and changing the pitch of the propeller. Figure 2-1 is a list of different designs for electric propulsion and the vessels on which the design has been implemented.

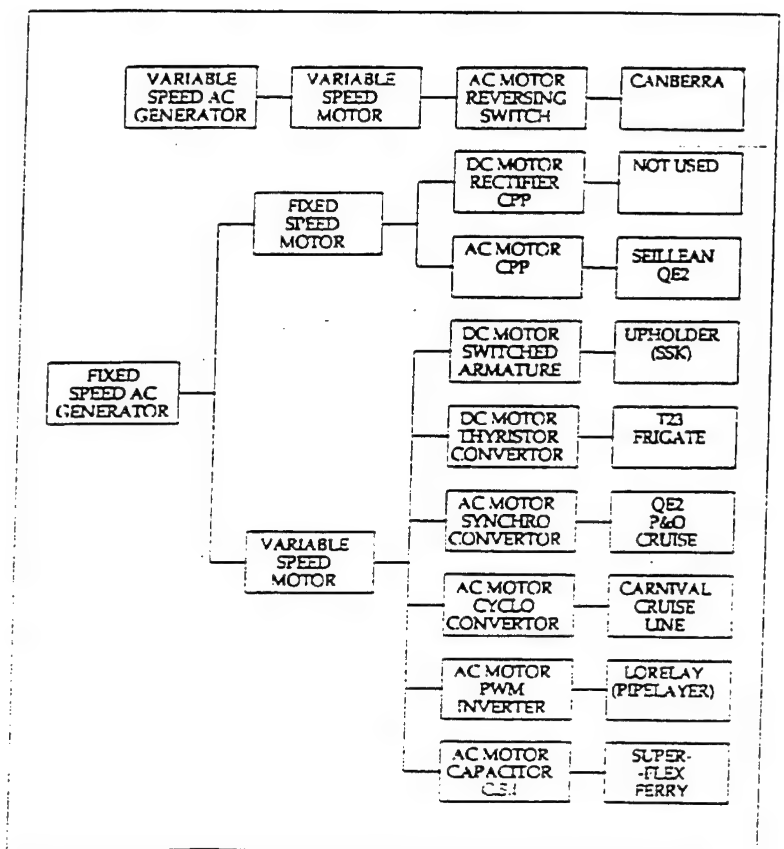

Figure 2-1. Various designs for electric propulsion [4].

4. Types of Prime Movers for Electric Propulsion

The first electric propulsion designs used diesel or steam turbines as the prime mover. Electric propulsion facilitated the use of high-speed prime movers, primarily steam-driven turbines, that were more efficient. A large number of diesel engines were used as prime movers for electric propulsion plants in low horsepower requirements. Diesel engines were used in smaller ships to save space and electric propulsion also allowed the diesel engine to operate at higher speeds for better efficiency. A small number of steam turbine electric propulsion systems built in the 1940's and 1950's are still in use today, primarily the notable T2 tanker. In 1990 the *S.S. Louisiana Brimestone,* a T2 tanker built in 1943, was still in operation. The progression toward smaller and more efficient prime movers has led to modern designs utilizing diesel or gas turbines. The size and operational requirements of the ship being built ultimately dictate the type of prime mover. Early prime movers operated with governor controls that would allow it to change speed and effect the frequency output of the generator. In current designs the prime movers run at a fixed speed and changes in frequency occur after the output of the generator.

B. THE INTEGRATED ELECTRICAL SYSTEM CONCEPT

The Integrated Electrical System (IES) concept is a relatively new concept compared with the use of electric propulsion. The basic idea is to use a ship's prime movers to provide power for ship's propulsion, ship's service electrical load, ship auxiliary propulsion and other shipboard electric power users. IES represents the layout and controls for integrating the electric propulsion system with other systems using common electrical sources of power.

There are three primary reasons for the use of the integrated electrical ship concept. First, it will reduce the need for separate large ship's service generators. Second, allowing prime movers to be used for several different systems reduces cost by reducing the total number of prime movers. Third, the system provides increased redundancy. The advantages of the overall system are reviewed in detail in Chapter III.

III. ADVANTAGES AND DISADVANTAGES OF ELECTRIC PROPULSION AND THE INGETRATED ELECTRICAL SYSTEM

A. ADVANTAGES OF ELECTRIC PROPULSION AND INTEGRATED ELECTRICAL SYSTEM

1. Advantages of Electric Propulsion

There are many attractive advantages for using electric propulsion for ships. The advantages particular to electric propulsion are divided into the areas of design, operation and cost savings. The following advantages are given for electric propulsion.

- Increased cross-connect capability creates greater redundancy for the engineering plant. - With electric propulsion a main propulsion prime mover and generator can be cross connected to any shaft, to the ship's service electrical load or to auxiliary systems without the need for additional equipment. In contrast direct drive propulsion systems can only provide power to the shaft to which it is attached. In addition, there is no way to provide power to ship's service electrical loads or auxiliary systems without power take-off's or other equipment [1,5].
- Electric propulsion provides greater reliability. - Reliability is improved by being able to use any prime mover and generator to power any propeller. With direct drive the failure of the prime movers attached to a specific shaft results in a loss of partial or all power on that shaft. With electric propulsion, power can be supplied from any prime mover to any shaft increasing reliability of the propulsion system. [5].
- Ship layout and engineering plant positioning can be more flexible. - Prime movers for shafts no longer have to be located to provide direct coupling to the shaft. An electric propulsion design would allow prime movers be located higher in the hull allowing improved ship design [1,5].
- Increased survivability can be gained from the cross-connect capability and the flexibility in design and layout. - With the flexibility to place prime movers and generators in separate spaces the loss of one space does not cause the loss of several prime movers and generators . The ability to cross connect increases the number of paths that can be used for a prime mover and generator to supply loads [1,5].

- Propulsion system control is improved, providing a simple and rapid reversal. - Speed can be controlled infinitely variable by using electronics to adjust frequency. Reversing can be initiated by changing the sequence in which the electronic devices in the power converter are gated or by the use of a controllable pitch propeller. In contrast, the majority of gas turbine direct drive propulsion systems use a mechanical governor on the prime mover and a controllable pitch propeller for speed and reversing control. The governor controls on the gas turbines rely on mechanical connections which may become worn leading to maladjustment. Diesel and the remainder of the gas turbine direct drives use mechanical governors and reversing gears. This design uses a more complex and larger gear box to provide a pinion for reversing. A steam turbine uses mechanical controls and a separate reversing turbine. With a steam turbine the power for reversing is limited by the use of smaller less efficient astern turbine elements [5].
- Electric propulsion provides quiet operation. - The prime mover for electric propulsion is not directly coupled to the shaft and, as such, the mechanical vibrations from the prime mover and large reduction gears are eliminated [1,5].
- Improved fuel economy is provided with electric propulsion. - The prime movers can be operated at more efficient speeds and to its maximum rating. Direct drive propulsion is constrained by reduction gears and shaft limitations from the prime mover to the propeller [5].
- Reduced cost in maintenance. - Reduced cost for maintenance is gained by running prime movers at a constant speed reducing mechanical stresses which in turn minimizes the failures of moving parts. Also, if prime movers are operated at full load there will be a reduction of operating time for each prime mover. This increases the time between overhauls and the period between required maintenance. It is generally realized that electric equipment costs less to operate and maintain than mechanical equipment. In particular the comparison would be between the reduction gears and the converter and motor operation [1,5].
- Flexibility in the types of prime movers used on the same ship. - Electric propulsion is not concerned with the operating characteristics of the prime movers providing power to the generators. An example would be the use of two diesel engine driven generators and one gas turbine driven generator on the

same ship. The output speed and operating characteristic of the two different prime movers could be very different in turn making the speed reduction to the propeller in a direct drive propulsion system very difficult. In the case of an electric propulsion system as long as both prime movers can drive a generator to produce a specified voltage and frequency, the system will work with no increase in equipment or operational difficulty.

2. Advantages of an Integrated Electrical System

The advantages gained through integration of an entire ship's electrical system only further support the use of electric propulsion. The advantages for the IES are provided below.

- Adaptability for multiple uses of the prime mover and generators. - With an IES electrical power from the main propulsion prime movers and generators can be used for many purposes. Electrical power can be provided to the ship's service electrical system. The main propulsion prime movers and generators can provide power to auxiliary drives, cargo equipment, weapons system, etc. [1]. The only requirement is for the components that are being supplied power from the IES be electric.
- There will be a reduction in the number of prime movers required for ship's service electrical system. - Dedicated ship's service electrical generators to support the entire ship's service load and the number of generators to provide redundancy for the ship's service electrical system are not required. The unused space may be allocated for other purposes. (Note: Separate small generators for ship's service electrical loads may be provided for economic operation in port.)

B. DISADVANTAGES OF ELECTRIC PROPULSION AND AN INTEGRATED ELECTRICAL SYSTEM

1. Disadvantages of Electric Propulsion

As in any technological compromises, there are some disadvantages to electric propulsion. The disadvantages of an electric propulsion system include.

- Efficiency between the prime mover and the shaft is reduced. - Any time a change in the form of energy occurs there is generally a loss. In the case of a direct drive, the losses introduced by the mechanical transmission are less than those introduced in an electric propulsion system where power is

converted from mechanical form to electrical form, manipulated, then converted back to mechanical form [1]. The additional stages of energy conversion usually translate into an efficiency of about 91% as compared to direct drives whose efficiencies are on the order of 97 percent [5].

- There is an increase in space and weight required for the electrical equipment. - With electric drives increased space is needed for propulsion generators, wiring, frequency converters and propulsion motors. With the addition of equipment there is an increase in weight for the propulsion system.
- Power quality problems occur. - Harmonics in the electrical system are created with the use of converters. Harmonics in the propulsion motor are in turn transmitted to the shaft which radiates out as noise and increased signature [6].

2. Disadvantages of the Integrated Electrical System

Disadvantages of the integrated electric system are as follows.

- Efficiency of the system is reduced. - The number of stages for the power to get from the prime mover to the equipment using the power is increased, reducing the efficiency.
- Control of the system becomes more complex. - With added power converters comes added flexibility in terms of control; however, the development of the individual systems to maintain stability are complex endeavors.

C. ELECTRIC PROPULSION FOR THE U. S. NAVY

The advantages listed above all support the U. S. Navy's drive for developing an electric propulsion system. In a more detailed review, there are more far-reaching effects on the U.S. Navy than can be seen in the list of advantages. There has been a tremendous drive in the U. S. Navy to reduce costs in the procurement, operation and maintenance of its fleet. To this end electric propulsion and the IES are seen as the probable choices for the future. The commonality between components on different classes of ships using electric propulsion and the IES reduces personnel training, minimizes the different types of spare parts required and reduces procurement costs. In addition, the development of high-energy weapons and electro-magnetic aircraft launching systems will necessitate large increases in available power. With

the need to reduce cost, save space and reduce manning, there will not be large separate prime movers and generators made available for these systems. The power for these systems would be provided by the main propulsion prime movers and generators or a combination of ship service and main propulsion prime movers and generators depending on the requirements of the individual system.

In order to illustrate the practical differences between a current ship layout including direct drive propulsion and a radial AC ship's service distribution system, and a ship employing electric propulsion and an IES, the following operating and design characteristics are listed.

I. Current U.S. Navy Guided Missile Frigate FFG-7 Class with direct drive and separate Ship's Service Electrical System (SSES) has the following [7]:

- Single shaft utilizing a controllable pitch propeller.
- Two main propulsion LM 2500 Marine Gas Turbines each rated at 20,000 HP for direct drive to a single gear box.
- Both LM 2500 located in one space with reduction gears.
- Four ship's service diesel generators each rated at 1000kW.
- Diesel generators located in four separate spaces.
- Ship's service electrical power is provided by the four ship's service generators.
- Two 650HP Electric Auxiliary Propulsion Units (APUs) located forward in two separate spaces.
- The two APUs are power from the ship's service electrical system. When the APUs are in use three ship's service generators will be in operation to provide for the higher electrical load.

II. One possibility for ship design employing electric propulsion and an IES

- Single shaft utilizing a controllable pitch propeller.
- Two LM2500 Marine Gas Turbine generator sets rated at 2,700 HP each.
- Each LM2500 generator set located in its own space.
- Two frequency converter units rated at 22,000 HP in separate spaces.
- One 20,000 SHP double wound synchronous motor directly attached to the shaft, no reduction gear, located in the same space.
- Two ship's service gas turbine generators each rated at 1500 kW.

- The two ship's service gas turbine generators are located in separate spaces.
- Ship's service power is provided by any of the prime movers via a main bus that feeds both ship's propulsion and electrical loads.
- Two 650HP APUs located forward in two separate spaces.
- The two APUs are powered from a main bus that feeds both propulsion and ship's service electrical load and can be supplied power from any of the prime movers.

III. Second possibility for ship design employing electric propulsion and an IES

- Two shafts utilizing fixed pitch propellers.
- Four main propulsion gas turbine generator sets each rated at 13,500 HP.
- Each main propulsion gas turbine generator set is located in its own space.
- Four frequency converter units rated at 11,000 HP in separate spaces.
- Two 20,000HP double wound motors directly attached to each shaft, no reduction gear, located in separate spaces.
- One ship's service gas turbine generator rated at 1,000kW.
- Ship's service gas turbine generator located in own space.
- Ship's service power is provided by any of the prime movers via a main bus that feeds both ship's propulsion and electrical loads.
- Two 650HP APUs located forward in two separate spaces.
- The two APUs are powered from a main bus that feeds both propulsion and ship's service electrical load and can be supplied power from any of the prime movers.

From the three examples above, it is clear that electric propulsion with an IES can reconfigure spaces, change the number of prime movers, modify the ratings of the prime movers, and alter the ship configuration while maintaining the same power output required for a specific ship design. In Table 3-1, a simple analysis is presented on how a current direct drive propulsion system with a typical AC ship's service distribution system can compare to an electrical propulsion and an IES. Shown in Table 3-1 are the different numbers and ratings of prime movers that can be used with electric propulsion and still

provide for the requirements of propulsion and electrical load compared to a direct drive with a separate SSES.

	Current Direct Drive with separate SSES	Electric Propulsion with an IES (Number 1)	Electric Propulsion with an IES (Number 2)
Number of Propulsion Prime Movers (Rating)	2 (20,000 HP)	2 (20,700 HP)	4 (11,010 HP)
HP from Propulsion Prime Movers	40,000 HP	41,400 HP	44,040 HP
Number of Ship's Service Electrical Prime Movers (Rating)	4 (1340.5 HP)	2 (2,011 HP)	1 (1340 HP)
HP from Ship's Service Electrical Prime Movers	5,362 HP	4,022 HP	1,340 HP
Total Horsepower from all Prime Movers	45,362 HP	45,422 HP	45,380 HP

Table 3-1 Comparison for different numbers of prime movers and ratings to result in same total output.

In the following chapter, the components that are utilized for an electric propulsion system and an IES are presented. With each type of component presented the various options in design that are currently available or under development are introduced.

IV. COMPONENTS FOR ELECTRIC PROPULSION AND INTEGRATED ELECTRICAL SYSTEM

This chapter includes an introduction to the different alternatives for each electric propulsion and Integrated Electrical System (IES) component and the options available for the system architecture. An overview is provided for the operational characteristics of the various components that are introduced. This section also contains a review of the electrical power distribution for the propulsion system and Ship's Service Electrical System (SSES).

A. COMPONENTS FOR ELECTRICAL PROPULSION

1. Prime Movers for Electric Propulsion and IES

The first item considered is the prime mover for the propulsion generators. A prime mover is one of the three common items found in an electric propulsion system. Currently there are four primary types of prime movers used in the U.S. Navy: gas turbine, conventional steam turbines, diesel and nuclear steam turbines. The most common main propulsion prime mover is the LM2500 Marine Gas Turbine produced by the General Electric Corporation. These are found mostly on surface combatants and the new class of fleet support vessels. The LM2500 comes in two basic types the 20,000HP and 25,000HP versions. Current direct drive systems have two LM2500 Gas Turbines outputting to a reduction gear set. The reduction gear set has an output to a single shaft. The direction of thrust is controlled with a controllable pitch propeller or through a reversing pinion in the reduction gear.

The second type of prime mover is the conventional steam turbine. These steam turbines use combustion boilers to provide steam for main propulsion turbines and ship's service turbine generators. The turbines operate at speeds in the thousands of Rpm's. The steam turbines output to a reduction gear set. Reversing is accomplished by using a separate turbine that rotates the shaft in the opposite direction. The reversing turbine produces considerably less power than the forward turbine. The shaft is normally fitted with a fixed pitch propeller. These types of prime movers are found on aircraft carriers, amphibious ships, command and control ships and numerous fleet support ships.

The third type of prime mover includes medium-speed diesel engines. These are primarily used in amphibious ships. The medium-speed diesel also uses a reduction gear like the gas turbine and steam turbine. However, reversing can be accomplished with a reversing pinion inside the reduction gear or through the use of a controllable pitch propeller. The fourth type includes nuclear steam turbines. This type of prime mover uses a nuclear reaction to create steam for the main propulsion turbines and ship's service turbine generators. Nuclear steam turbines operate like conventional turbines. These types of engineering plants are found on aircraft carriers, submarines and a few surface combatants.

Any of these prime movers can be used with a generator to provide electrical power for propulsion and an IES. When deciding on the type of prime mover, ship design and the operational requirements are the main factors. This is uniform for both the direct drive and electrical propulsion. There are four areas to be reviewed in choosing a prime mover. The first consideration is the size of the prime mover. In the case of conventional or nuclear steam turbines, the entire propulsion system is used for size determination. The second consideration is the fuel economy of the prime mover. In the cases of gas turbines and diesel engines there is a tradeoff between fuel economy and size. Gas turbines are lighter, but are not as fuel efficient as diesel engines. A third issue is weight, including the weight of the prime mover and the ship's structure or enclosures that support these prime movers. In the case of the LM2500 Marine Gas Turbine, its total weight is 44,500lbs while the Gas Turbine unit itself only weighs 11,000lbs [8]. For steam plants the prime mover weight would include the ship structure that encloses the engineering plant. The fourth determinant for choosing a prime mover is operating cost. This includes manning, repair and spare part cost. In some cases the operating cost and space requirements are secondary for the prime mover when design requirements imposed by other systems are the driving factor. For example, aircraft carriers require steam for catapults to launch aircraft so conventional or nuclear steam turbines are used as the prime mover even though these type of prime movers are large and costly to operate. Special requirements that drive the type of prime mover do not effect the basic operation of the electrical propulsion system or the IES. However, the best case would be for all systems to be supplied power from the IES. This would eliminate restrictions placed on the type of prime movers due to ship's system requirements.

2. Generators for Electric Propulsion and IES

Once a prime mover has been determined the next step in electrical propulsion system design is to conduct a tradeoff study to determine the optimum shaft speed, considering both prime mover and generator operation. The design of a generator should support operation of the prime mover at its most efficient speed and should, where possible, use direct coupling so as to reduce the weight and volume of the system. Also, direct coupling reduces the underwater acoustic signature produced by the reduction gears. These are prominent advantages to using electric drive. If efficient operation of a steam turbine occurs at 4,200rpm, a generator would be designed to operate at that speed. Also, as the design progress continues the output frequencies of the generator will also affect the remainder of the components of the electrical propulsion system and the IES.

The generator has many more design and operational requirements placed on it than the prime mover. First, the physical characteristics of the generator are considered. The most common generator design is a rotating armature that is turned by the prime mover inside a stationary stator. The output voltages are taken directly off the stator windings. The limiting factors for this generator architecture are the dynamic forces that the rotor can handle at a given speed and the number of poles that can be placed on the rotor due to size limitations of the stator. The relationship between the speed of the rotor and output frequencies is also effected by the number of poles. With the number of poles effecting the size of the generator's rotor, a detailed stress and rotor dynamics study should be conducted to determine the upper speed limit of a generator [8]. With a fixed number of poles and speed limit established, the maximum frequency of a generator can be determined. Benefit can be gained through the employment of high-frequency supplies. The benefits include reduced size and weight of the generator and a reduction in the harmonic distortion throughout the IES caused by various electrical converters [9].

There are other generator designs that are available and considerable work has been done in reducing the size and weight while increasing the power density of the generators. Power density is the amount of power per unit volume. Other designs which are currently being studied and produced on small scales are the permanent magnet generator, the cup type generator and the superconductive generator [2,10]. The first type of generator design is the permanent magnet generator. These generators use a

permanent magnet to provide the flux field instead of the armature having windings that are electrical excited to produce the flux field. The cup-type generator has the rotor in the shape of a cup and is external to the stator. The cup-design generator under development uses permanent magnets in place of an electrical excited wound rotor. The cup design, together with high-speed operation, allows the production of a higher frequency and an overall weight and size reduction over a conventional generator design [10]. The cup generator has limitations on the rotor speed due to mechanical forces, very similar to a conventional design, and on the size and number of phase windings that can be placed in the stator due to the cup surrounding the stator.

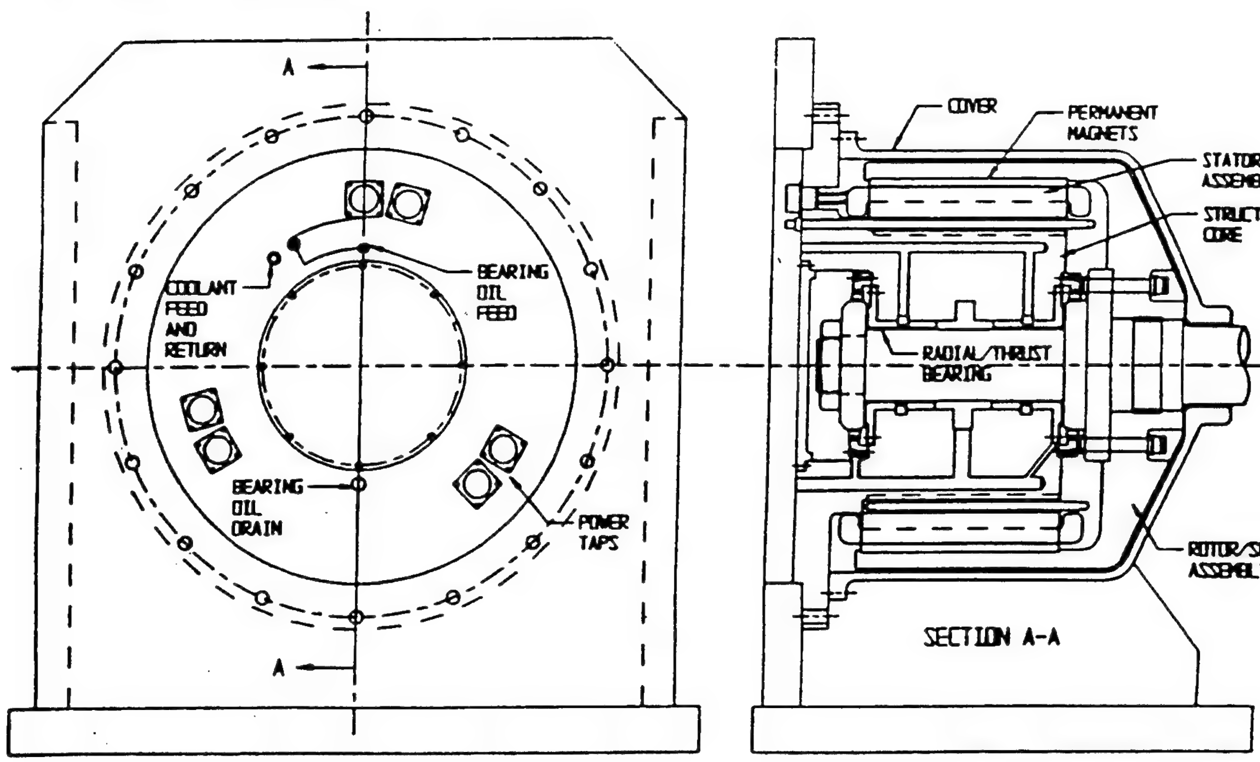

Figure 4-1. A proposed 15MW permanent magnet cup generator[10]

The superconductive generator is a super-cooled generator that uses special materials, such as niobium-titanium, in the stator and rotor and that has a very high power density [1]. That is, a large amount of power is realized from a very small machine.

Other features of the generator design include selection of the number of phases, voltage, amperage rating and method of cooling. These operating characteristics are determined by the components of the electrical propulsion system and the components of the IES. The generator design must take into

consideration the harmonic loading that are dictated by the type of frequency converter to be used for the propulsion motors, the motor design and the electrical system distribution. In the IES, tradeoffs occur between the optimum generator design and the operating characteristics for different components that the generator must support. These tradeoffs that occur between frequency, voltage, amperage characteristics and the number of phases and the harmonic reduction are reviewed in detail in Chapter V.

3. Converters for Electric Propulsion

The next component to be considered in the electrical propulsion design is the frequency converter for the main propulsion motors. There are four basic types of converters appropriate for use in DC or AC electric propulsion: the Graetz converter, AC-to-DC rectifier; the cycloconverter, an AC-to-AC voltage source converter; the synchroconveter, a type of current source DC link converter; and the pulse width modulation (PWM) converter, a type of voltage source DC link converter [11]. Within these types there are several different configurations. The objective is to select the best converter type based on efficiency, power density, size, operational characteristics with the required type of propulsion motor, electrical harmonics and cost. By requiring that the electrical energy be processed through a power converter then through an electromechanical machine, an electric propulsion alternative tends to be less efficient in power transmission than a comparable direct drive. As is expected, there are numerous advantages and disadvantages for each type depending on operational requirements. The issues regarding converter design and operation are fully explored in Chapter V. Figure 4-2 represents the four basic types of variable speed propulsion system arrangements.

4. Motors for Electric Propulsion

Integral to the selection of the power converter is the selection of the main propulsion motor. There are a number of candidates available for use on board ship: the induction machine, the wound-rotor synchronous machine, the permanent magnet synchronous machine, the transverse flux permanent magnet synchronous machine, the switched reluctance motor and the homo-polar motor. Of the machines

previously listed, the DC machine, induction machine and the wound-rotor synchronous machine are the ones currently being used shipboard.

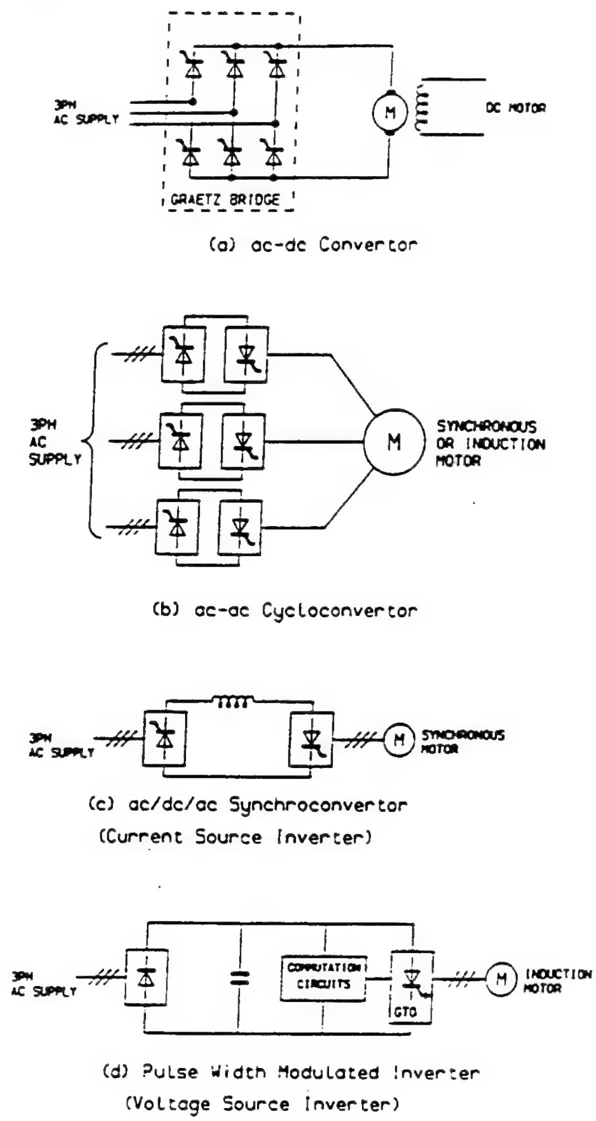

Figure 4-2. Variable speed system arrangements for propulsion [11].

Wound-rotor synchronous motors are widely used for high power and large torque applications; however, there are several drawbacks in terms of size, weight, maintenance and efficiency. There has been

tremendous advances in the field of permanent magnet machine technology. In the last five years research by an industrial consortium and involving the U. S. Navy led to the manufacture of a prototype permanent magnet motor. The consortium intends to build a second permanent magnet motor rated at 9.5 MW by late 1998 [2]. The advantages offered by a permanent magnet motor are an increase in power density and a reduction in maintenance. The power density is gained by replacing the wound rotor with a smaller rotor containing permanent magnets. Reduced maintenance is realized by eliminating the need to electrically excite the wound rotor. The biggest drawback is the heat produced in operation and the effects of electrical harmonics on its operation. The transverse flux and homo-polar motors both are designed to increase power density. Figure 4-3 shows one form of a transverse flux motor where the stator loops are arranged around the stator winding and permanent magnets are located on the rotor. There are several designs being considered for the transverse motor. Figure 4-3 represents the most basic form. The transverse flux motor development is underway in the U. K. and the homo-polar motor is being studied at NSWC in Carderock, MD [1,12].

B. DISTRIBUTION ARCHITECTURES FOR ELECTRICAL PROPULSION AND THE IES

Having addressed the prime movers, the generators, the electric propulsion frequency converters and individual propulsion motors, the final aspect of the electrical propulsion and the IES is the interconnection and power distribution. There are three prominent architectures for the distribution system for electric propulsion and the IES. The first option employs AC generators that distribute AC electrical power on a main bus that is in a ring or linear configuration. From the main bus the AC power is distributed to the propulsion motor converters and other loads like the ship's service electrical system and maneuvering thrusters. Figure 4-4 represents a typical propulsion system where AC generators provide power to a linear main bus which feeds various loads. In this figure, only propulsion is shown being supplied from the main bus.

The linear bus architecture is most commonly used today with electric propulsion and the IES. The second architecture uses a DC distribution bus. The generators still produce AC electrical power which is immediately rectified to DC. The DC electrical power is then distributed on a main bus in a ring

configuration for use by all electrical loads. Once at the loads the DC electrical power is converted to the specific form of electrical power needed by that component. For example, the propulsion motor converters will change the DC electrical power to the required AC electrical power at the correct voltage and frequency. The third design uses AC distribution for the electrical propulsion load and DC distribution for the ship's service electrical loads.

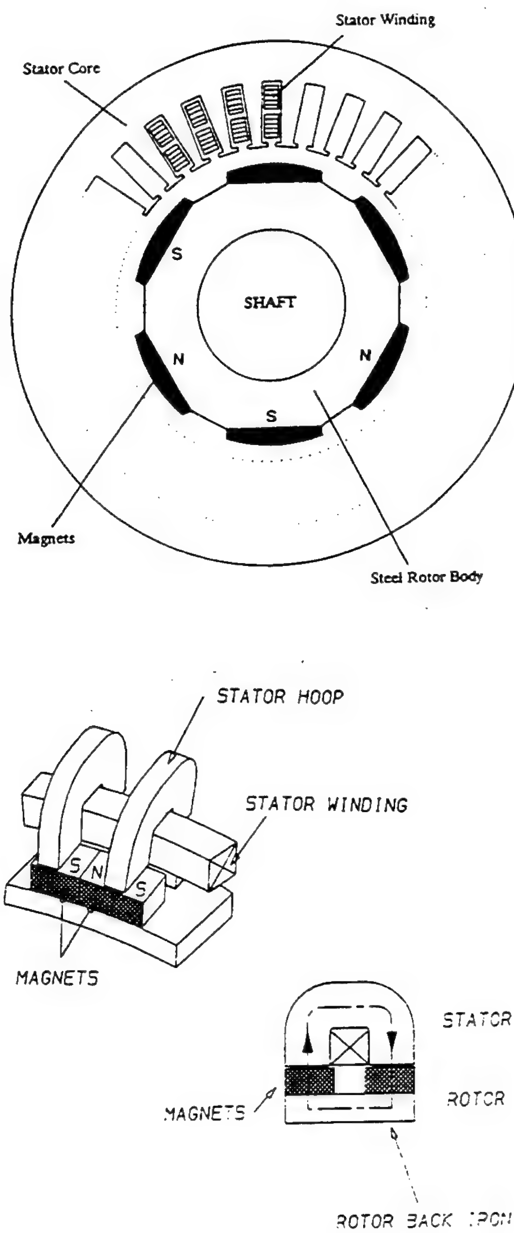

Figure 4-3. One form of a transverse flux motor: single-sided stator, surface-rotor-mounted magnets[12]

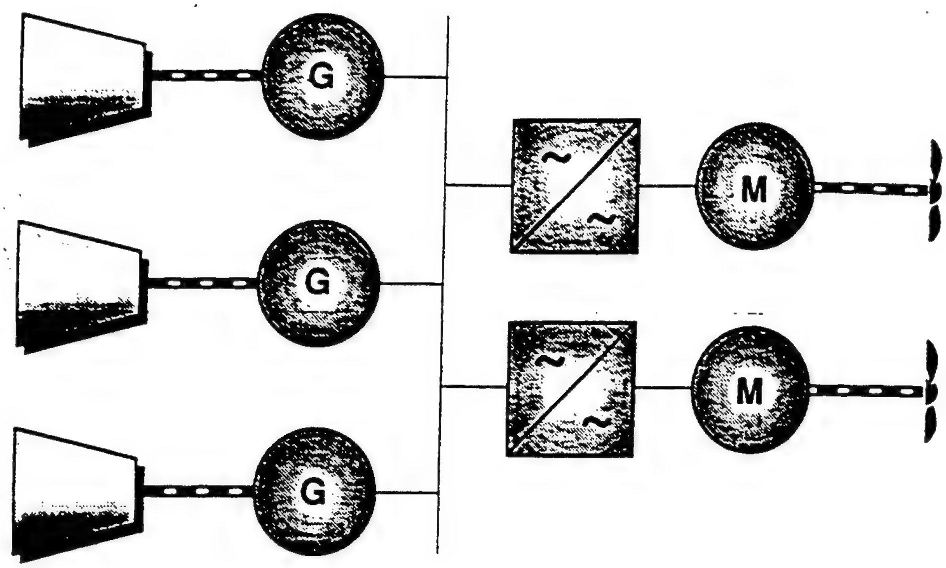

Figure 4-4. Typical propulsion system (integration with IES not shown) [4]

C. SYSTEM REQUIREMENTS FOR SHIP'S ELECTRICAL LOADS

1. Compatibility for the Integrated Electrical System

With an IES all of the ship's electrical loads are supplied from a main bus or directly from generators depending on the operating condition of the ship and the electrical load. There are three topics that need to be addressed with the ship's service electrical requirements. First, the size and nature of the ship's electrical loads must be evaluated to determine the load that will be placed on the main bus and the ship's generators. The main propulsion generators and the ship's service electrical generators must have the appropriate capacity and redundancy to support the ship's electrical loads during all operating conditions. The second topic is the method of connection for the ship's electrical loads to the IES. The type of connection will be driven by the distribution from the generators and will effect the third topic. The third topic is the architecture that will be used to supply the ship's electrical loads. The ship's electrical distribution architecture is the method in which the ship's loads are supplied throughout the ship. As previously stated in Section B, there are three architectures being considered for the IES.

2. Integration of the Ship's Service Electrical Load

The first issue is the ship's service electrical load. The load will be very dependent on the size and type of ship. There are certain design characteristics that have been used to build an independent ship's service electrical system [10]. These design characteristics involve the amount of electrical power that can be supplied in relationship to the load, the number of electrical power suppliers and the amount of overload capacity each supplier can provide. All of these design attributes figure into the development of the electrical propulsion generators, the capacity and number of supply connections to the ship's service load and the specification of the ship's service generators.

The second issue is the characteristics of the ship's service electrical system in terms of voltage levels and, for AC distribution, frequency. As described in Sections A and B of this chapter there are several different distribution architectures available for the electrical propulsion system. For an IES design to work, the ship's service electrical distribution must be compatible with the electrical propulsion system. An example of this is a propulsion generator providing the electrical propulsion system with 6.6kV at 120Hz via a main bus. If the ship's service and its various loads require AC power of 450V at 60Hz, the supply from the main bus must be modified to meet the requirements of the ship's service electrical system. The same issues apply if generators of various power ratings will be part of the IES. The generators need to have the same frequency and voltage outputs or have their outputs changed to be common with the IES design. An architecture that will allow common sources to supply electrical power to all users is one of the corner stones to the implementation of an IES.

A third issue involves the selection of the ship's service distribution architecture. There are two architectures being considered for ship's service electrical distribution in an IES. The AC distribution system which provides AC power from the source to the user. This system is the most widely used today. The second system is the DC zonal system. This system has DC electrical power provided to a bus that is distributed to different zones in the ship where the voltage is regulated to a desired level. Inside the zone the DC electrical power is distributed and converted to AC electrical power for use by various electrical components. This system provides a weight savings and better survivability than the traditional AC distribution architecture. The DC zonal architecture with its electronic controls provides simple current

monitoring, near instantaneous fault detection and rapid switch-over to alternate power sources. With AC distribution, several cycles are required before faults are detected. Power may be temporarily lost to critical combat system components before the AC distribution is able to switch to an alternate power source.

The final issue involves the means of supplying the ship's service electrical system when the ship is at anchor or in port with shore power available. The simplest way to overcome this problem is to provide the ship with small generators for use at anchor or in port. These same generators will be used to supply power as part of the IES during certain conditions. When shore power is available there must be a way to provide for the requirements of the ship's service electrical load. The shore power will either be directly fed into the SSES if already compatible or will be converted to be compatible.

3. Integration of Auxiliary Electrical Loads

There are many issues concerning the loads that will be incorporated into the IES. The main issues are how each load will be supported and the effect of each load on the system as a whole. The principle items that are considered for the auxiliary load are cargo handling equipment, thrusters for maneuvering, aircraft launching equipment and energy weapons. The same issues that apply to the ship's service electrical system apply to the auxiliary loads. The main propulsion and ship's service generators must be able to provide the electrical power to the auxiliary loads. In the case of auxiliary loads that are only to be used under certain conditions, the amount of electrical power which can be diverted from the propulsion and ship's service electrical must be quantified.

V. DETAILED ANALYSIS OF COMPONENTS FOR THE ELECTRIC PROPULSION SYSTEM

In this chapter the various components that comprise the electrical propulsion system are reviewed in detail. These include the propulsion generator prime movers, the propulsion generators, the propulsion converters, and propulsion motors. Each topology for the various components will be discussed in detail and the advantages and disadvantages to each type are addressed. For this analysis, a focus is placed on currently available technology.

A. ANALYSIS OF THE PRIME MOVERS FOR SHIP'S PROPULSION GENERATORS

1. Evaluation of Prime Movers

There are several issues that must be evaluated to determine the type of prime mover for the ship's propulsion generators. In Chapter IV the cost, size, efficiency, maintenance, manning and operational requirements were given as decision factors on the choice of prime movers for any type of propulsion system. Depending on the size and type of ship, the choice of prime movers may be driven by a specific factor that may out weigh the others. The previous example of an aircraft carrier requiring the use of steam catapults motivates the use of conventional or nuclear steam powered prime movers for the propulsion design. In comparison, the use of gas turbine prime movers has been driven by the reduction of weight and space for the prime movers, the ease of maintenance and the reduced manning requirements.

The same basic factors in the decision for a prime mover for a direct drive propulsion system apply to an electric propulsion system. All of the current primer movers that are in use with the Navy can also be used with electric propulsion. The most envisioned prime mover for the electric propulsion system is the marine gas turbine. The marine gas turbine has a low volume to horsepower ratio. The most widely used marine gas turbine for the U.S. Navy is the LM2500. Because of its wide use in the Navy and existing support and training infrastructure already in place, the LM2500 is the proposed prime mover to be used with the first generation of electric propulsion. The Navy is currently working with General Electric to use the very proven LM2500 Gas Turbine as the prime mover for its electric propulsion system.

Even though the marine gas turbine is currently the favored prime mover, the remainder of the Navy's other prime movers can still be used with an electric propulsion system. Currently, most commercial ship electric propulsion systems operate medium-speed diesels as the prime movers for the main propulsion generators [4]. The medium-speed diesels are fuel efficient over a broad range of operation and are very reliable; however, they have a much higher volume to horsepower ratio than do marine gas turbines. As previously discussed steam prime movers are still used when special requirements outweigh their drawbacks. As discussed in Chapter I electric propulsion was originally developed to provide speed reduction for propulsion systems using steam turbines. Steam prime movers can still be used with electric propulsion systems allowing continued use of nuclear power.

2. Analysis of the LM2500 for the Electric Propulsion Generator Prime Mover

Because the LM2500 is the most promising choice for the prime mover for the electric propulsion system, an analysis of its operation is detailed. One of the reasons to use electric propulsion is to operate prime movers at a more efficient speed [9]. This substantially improves fuel efficiency and thus enhances mission capability and emissions. Figure 5-1 and 5-2 are the estimated fuel curves for an LM2500. Figure 5-1 represents the operation in variable speed application and Figure 5-2 represents the operation in a constant speed application. For constant speed applications the LM2500 operates at 3,600 rpm. An LM2500 operates with a significantly higher efficiency above 2,800 rpm as shown in Figure 5-1 [7]. When using electrical propulsion, the LM2500 would have the highest efficiency at a constant speed of 3,300 rpm, but the use of the most efficient speed of a prime mover may not be possible due to other component operating characteristics.

Table 5-1 illustrates the fuel consumption for the direct drive propulsion system using a variable speed LM2500 operating between 1,800 rpm and 3,600 rpm producing between 5,000 HP and 25,000 HP compared to an electric propulsion system using an LM2500 operating at a constant 3,600 rpm producing the same horsepower.

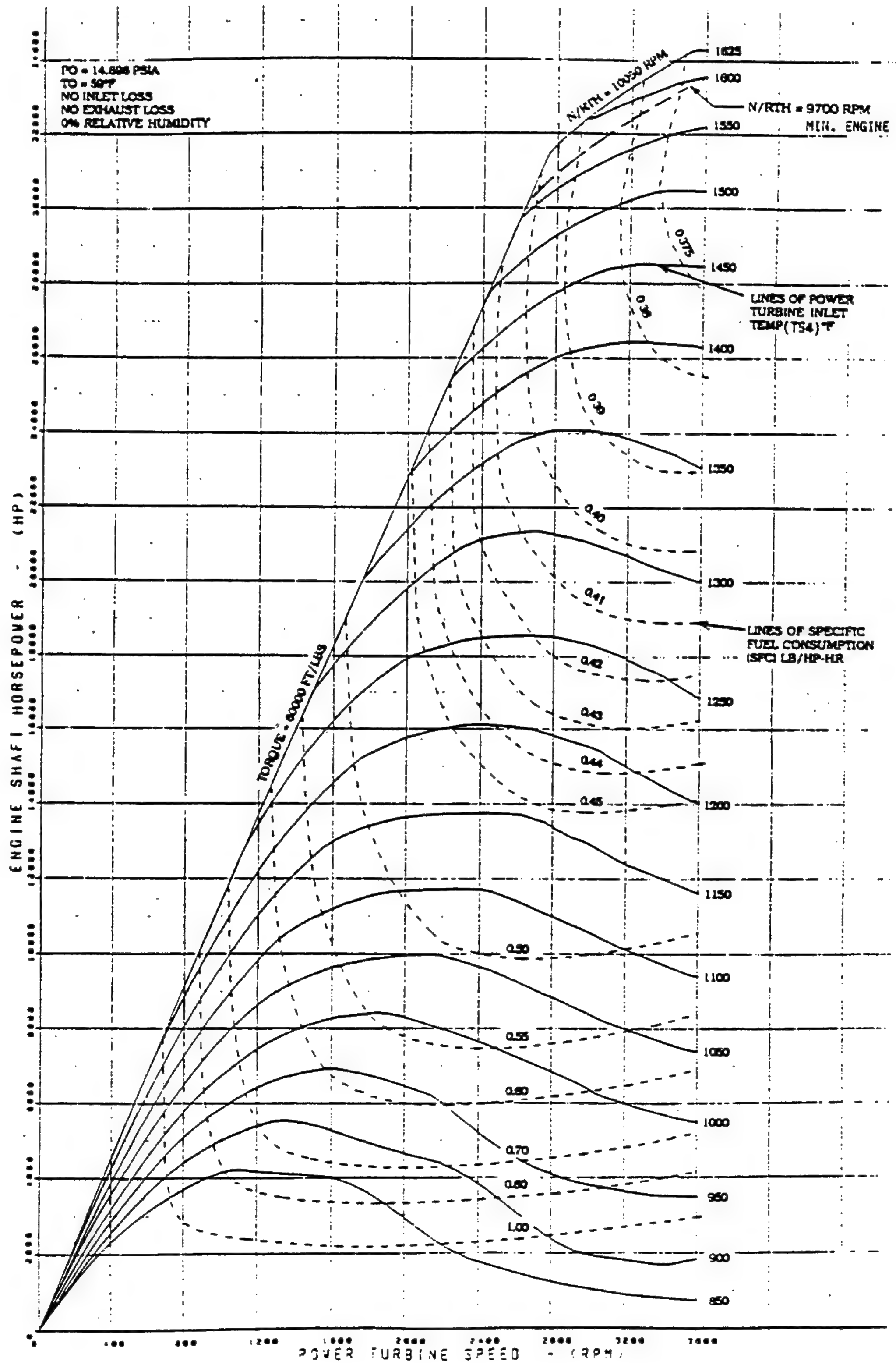

Figure 5-1. LM2500 Marine Gas Turbine estimated average performance operating at variable speeds [7].

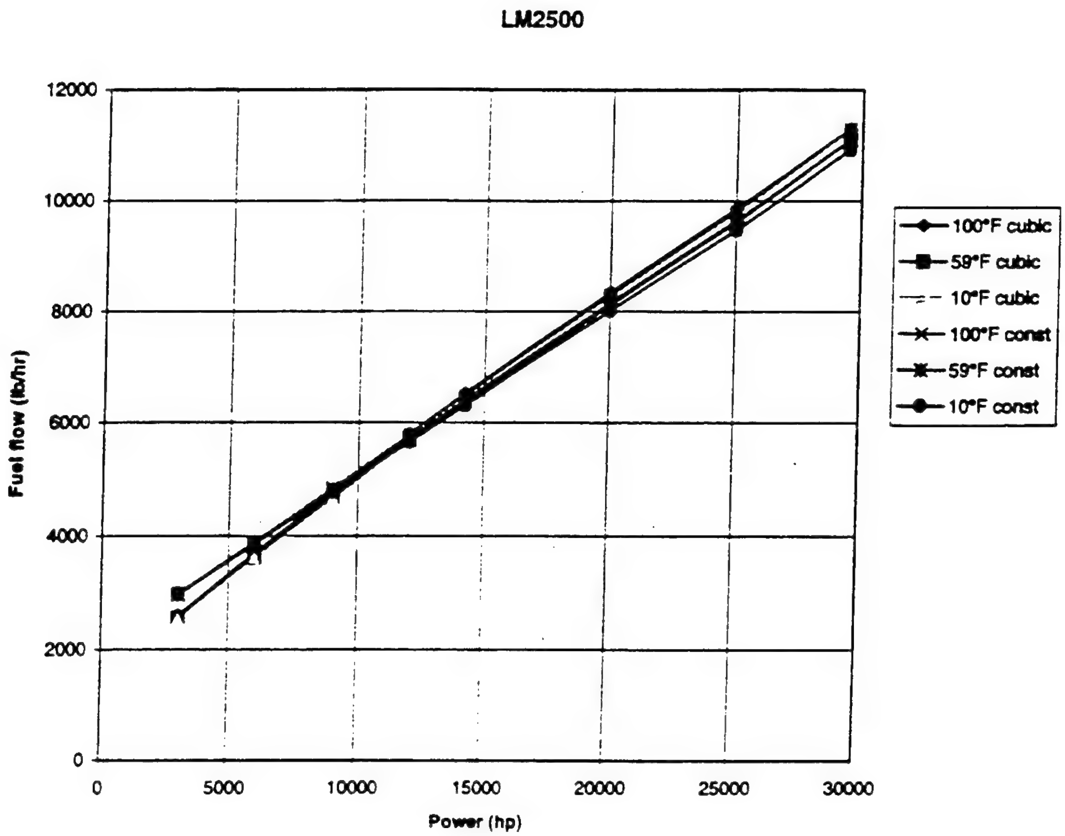

Figure 5-2. Estimated fuel consumption for an LM2500 operating at a constant speed of 3,600rpm [8].

Direct Drive's LM2500 rpm	Electric Propulsion's LM2500 rpm	Output Horsepower	Direct Drive Fuel Consumption (LB/HR)	Electric Propulsion Fuel Consumption (LB/HR)
1,800	3,600	5,000	3,500	3,100
2,250	3,600	10,000	5,400	5,000
2,700	3,600	15,000	6,750	6,500
3,150	3,600	20,000	8,200	8,000
3,600	3,600	25,000	9,750	9,700

Table 5-1 Comparison between direct drive and electric propulsion fuel consumption for a given rpm and horsepower.

The information for the fuel consumption comparison in Table 5-1 is taken from Figures 5-1 and 5-2. As is expected, the electric propulsion LM2500 uses less fuel than the direct drive LM2500 for the same delivered horsepower. This not only saves money in the purchase of fuel, it also enables the ship to be designed with smaller fuel tanks for the same performance in range and speed. The space and weight

reduction in fuel allows more weapons payload to be placed on a surface combatant and offsets the added weight of the electric propulsion system.

If a close examination is made of Figure 5-1, the most efficient speed of the LM2500 up to 25,000 HP is not 3,600 rpm, but closer to 3,300 rpm. In Figure 5-2, the fuel consumption data for the LM2500 being developed for electrical propulsion is shown operating at 3,600 rpm. Section B of this chapter contains an explanation or rationale for using the LM2500 at 3,600 rpm instead of the most efficient operating speed.

B. ANALYSIS OF THE MAIN PROPULSION GENERATORS

1. Design Issues for the Main Propulsion Generators

Generator design issues are addressed in this section. The prime movers in the previous section were to be used for constant speed operation and are connected to fixed-frequency electric generators. There are a number of physical characteristics that need to be considered when selecting a generator. These characteristics are affected by the operation of the prime movers which, in turn, effect the design and operation of equipment connected on the electrical side. This section lists these physical characteristics, analyzes choices for the design and provides for logical construction of a generator. In Chapter IV, a general review of the types of generators was provided which included physical characteristics and design characteristics. The physical characteristics will be dictated by current generator technology and by the most common and proven designs available. The most common generator in use today is the rotating armature inside the stationary stator with the armature being electrically excited: the field-wound synchronous machine. Other types of generators like the cup, superconductive and permanent magnet are in research stages and will not be considered for use in the generator design though these alternatives technologies offer substantial promise in terms of power density and reduced size.

2. Analysis of Prime Mover and Propulsion Generator Operation

When designing any generator, the desired speed of the prime mover and the required output frequency of the generator must be optimized to benefit both components. The connection designs

between the prime mover and generator can be direct coupled or indirect coupled through a set of gears. There are advantages to both designs. Using a set of gears allows the rotor of the generator to turn at a different speed than the prime mover. For high-speed prime movers, reduction gears can be used to reduce the rotor speed, reducing the dynamic forces on the rotor and for slow-speed prime movers, gears can be used to increase the speed to enable higher frequencies. The disadvantages of using gears include increases in acoustic noise levels, required space, weight and maintenance. One of the advantages to electric propulsion is eliminating the need for gears. For the purpose of this study the prime mover to generator connection is assumed to be a direct coupling. A key design issue, also an advantage in using electric propulsion, is to have the prime mover operate at the most efficient speed compared to a direct drive design. The speeds at which generators operate varies considerably from hundreds of rpm to thousands of rpm. The general rule is that physically larger sized machines operate at a slower speed than the smaller sized machines of the same horsepower rating. This follows from the fact that power is given by the production of torque and speed. Since a low-speed machines requires larger torque for a given horsepower, the larger torque necessitates larger currents which in turn requires larger conductors in the stator and bigger slots in the rotor. For the same output frequency the rpm's of the rotor can be reduced by adding more poles to the stator. The addition of poles increases the size of the generator. There is also a relationship between the speeds and the number of poles in a generator. The Equation 1-1 represents the relationship between frequency, poles and rpm.

It was proposed earlier that it was more advisable to operate the LM2500 at 3,600 rpm and not the most efficient speed of 3,300 rpm. The reason for using 3,600 rpm can be analyzed by using Equation 1-1 and setting the frequency output of the generator to 60 Hz, which is the common frequency for the United States and is currently being used in ship electric propulsion systems.

Setting N, the number of poles, to a value of two and f, the frequency, to 60Hz, and solving Equation 1-1 yields

$$n = \frac{f * 120}{N} = \frac{60 * 120}{2} = 3{,}600 \qquad \text{Eq 5-1}$$

From this result, a generator being directly coupled to an LM2500 producing 60 Hz would require the LM2500 to operate at 3,600 rpm. The operation of the LM2500 for electric propulsion using 60 Hz still provides considerable fuel savings over a direct drive system as proven by Table 5-1.

Varying the number of poles for a generator can also effect the operation of the prime mover and the output of the generator. If the number of poles is increased to four, the results for Equation 5-1 would be 1,800 rpm for the operation of the LM2500. The LM2500 operating at 1,800 rpm is considerably less efficient than operation at 3,600 rpm. If 120Hz was the desired output electrical frequency, a four-pole generator operating at 3,600rpm could be utilized.

3. Analysis of Operating Parameters for the Propulsion Generator

The voltage operating range of generators varies from hundreds to thousands of volts. The shore-based electric generation plants have generators that can produce voltages as high as 36kV [13]. Most marine applications, for example ship's service generators for a conventionally designed ship, operate at 450V line-to-line. The reasons for this wide range are numerous. Shore-based utility companies use high-voltage generators with transformers to deliver power over a vast network of power lines. For a given power to be delivered, these higher voltages reduce current and, in turn, reduce losses and voltage drops in the transmission lines. After high-voltage transmission lines reach their destination, a second set of transformers reduces the voltage to usable levels. However, on board conventionally designed ships the ship's service electrical generators can be dedicated to the ship's service load with short transmission lines. The need to reduce losses by using higher voltages with step-down transformers is eliminated. For electric propulsion and the Integrated Electrical System(IES), generator output voltages higher than 450V can and would be used for several reasons. The primary advantage of using higher voltages with electric propulsion is that the propulsion motors can be made smaller for the same horsepower. In the case of an IES where a DC distribution architecture will supply the ship's service load, no transformers are theoretically required since the AC voltage is electronically rectified to produce the desired DC voltage for distribution. The DC distribution system also eliminates the need for transformers to reduce the normal supply at 450V to 220V and 110V for other uses. The issues that limit the voltage rating of the generator

are the type of power electronics used in the AC/DC converters and propulsion frequency converters, the size of the propulsion motors and other electrical components ratings. Converters are addressed in the next section of this chapter.

The second design feature of the generator is the frequency. Most of the world use two frequencies in their terrestrial electrical power systems, 50Hz and 60Hz. The United States uses 60Hz. For shipboard use, 50Hz and 60Hz are also the two most widely used frequencies. Of the electric propulsion systems in use today the majority are 60Hz. The three leading companies in marine electric propulsion, CEGELEC; in the United Kingdom, ABB MARINE and STN ATLAS; both in Germany, all build a 60Hz, three-phase AC electrical distribution system [11]. There are several reasons for using 60Hz. First, the technology is mature, proven and available. No research and development, prototyping or expensive capital investment is required. Second, the electrical propulsion system can also supply power without the need for frequency conversion to the ship's service electrical load which principally requires 60Hz. The factors that will ultimately determine frequency are the physical limitations of the propulsion generator, the desired frequency range of the voltage supplied to the IES and the desired frequency range of the main propulsion converters. An issue that must be considered when determining frequency of the propulsion generator is the effect of the frequency on the SSES. Advantages of size reduction in components and reduced harmonics can be realized with a higher electrical frequency [6].

The next design features under consideration are the number of poles located on the rotor and the construction of the rotor. By using a different numbers of poles on the generator, output frequency can be changed without effecting the speed of the prime mover. The driving factors here are the prime mover speed, the physical size of the rotor and the desired electrical frequency output. The type of rotor to be used is the next point to analyzed. Rotor design is determined by the generator operating speed. The field-wound synchronous machine rotor normally has one of two designs: the salient-pole and nonsalient-pole, also called cylindrical rotor. In hydro-electric plants where the water pushing the rotor is moving relatively slow, there needs to be a large number of poles to produce the required frequency. The salient-pole design is better operated with numerous concentrated poles where slow speeds do not produce large dynamic forces on the rotor [13]. The non-salient pole or cylindrical rotor design operates with high-speed turbines.

They usually consist of a two or four-pole forged rotor [13]. However, designs of non-salient pole rotors are available with up to eight poles [13]. The generators to be used with electric propulsion and the IES will be non-salient pole design because of the use of the high-speed gas turbines as the prime movers.

C. ANALYSIS OF THE PROPULSION MOTOR FREQUENCY CONVERTERS

1. Types of Power Electronics for Frequency Converters

Before the types of converters are introduced and analyzed, a brief summary of the different types of electronic devices is presented. One of the main reasons that electric propulsion has been re-introduced into the mainstream of marine propulsion is due to the advancements in power electronics. The power electronics era has its beginning in 1957 with the introduction of the Silicon Controlled Rectifier (SCR) commonly called a thyristor [14]. With the introduction of the SCR, a departure from using rotating and static magnetic amplifiers to implement power control was possible. There are numerous electronic devices that are used today in power converters: the SCR, the Gate Turn-off Thyristor (GTO), bi-directional gate-controlled thyristors (TRIAC) , Bipolar Junction Transistors (BJT), the Insulated-Gate Bipolar Transistor (IGBT) and the Metal-Oxide Semiconductor Field Effect Transistor (MOS-FET) [14]. Additional technologies are actively being researched including MOS-Controlled Thyristor (MCT) and Silicon-Carbide technology (SiC). Discussion here is reserved to the more mature technologies listed previously. These devices all have their limitations and individual advantages. Of the power electronic devices listed above, three are primarily being used in high power converters: the Silicon-Controlled Rectifier (SCR), the Gate Turn-off Thyristor (GTO), and the Insulated-Gate Bipolar Transistor (IGBT). Applications of these devices range from small land-based to large marine-based converter units [11].

The most common device used in contemporary converter types is the SCR. The thyristor works on the principle of natural commutation. Chapter VIII will provide detailed information on natural commutation operation. When the voltage across its anode-cathode is reversed and the current passing through it decays to nearly zero, the device will naturally turn off. Device turn-on is initiated when the device is forward biased and an appropriate signal is applied to its gate. Voltage control is achieved by

delaying this gate signal from the point of natural commutation. The thyristor is available with voltage ratings from 50V to 5000V, and with a current carrying capacity ranging from 1A to 10,000A [11].

The next most widely used power electronic device is the GTO. The GTO uses forced commutation. A GTO is externally similar to the SCR in operation except that it may be turned off with a negative gate current. An advantage is the ability to turn off the GTO by gate control and not have to rely on natural commutation. This makes the need for some auxiliary circuits containing commutation capacitors and thyristors no longer necessary. However, it takes a considerable amount of negative gate current to turn the device off. This also requires the GTO to have more complex control for device turn off and turn on. The GTO operates in ranges from 50V to 3,000V. The power range of the converters using GTO components is limited to 8MW [11].

The relative newcomer to power converter technology is the IGBT. The IGBT is already widely used in small converter applications. The advantages to the IGBT are higher switching frequencies, lower losses and simpler control circuits than the GTO [14]. The drawback to the IGBT is the maximum voltage rating of around 1,600V. However, technology is being developed rapidly for rated values of 2,500V. The maximum foreseen voltage levels for IGBTs is anticipated to be on the order of 5,000V [20].

There are five items that must be taken into account when choosing the power electronic device used in the converter. These items are power rating of the device, type of commutation, the switching frequency, controls required and the efficiency.

2. Topologies and Design Considerations of Frequency Converters

Once the type of electronic device is chosen, the converter topology is then determined by the needs of the system. A converter is the part of the electric propulsion system which provides variable frequency electrical power to the propulsion motor. The converter processes either fixed DC or AC input voltages and delivers DC or variable frequency voltage to the propulsion motor. The two main tasks of the converter are to convert the voltage and current of the supply generator to the requirements of the motor and control power flow from the supply generator to the motor [14]. As previously stated, DC motors for high-power electric propulsion systems are not used and will not be considered in this thesis.

There are a variety of converter configurations for use with large AC motors. All of these converters work on two principles. The two principles are AC Voltage Source Rectifiers (AC VSR) and DC Voltage Source Inverters (DC VSI) [14]. The AC VSR is equivalent to a DC Current Source Inverter (DC CSI). The DC VSI is equivalent to an AC Current Source Rectifier (AC CSR). Line and motor-commutated AC VSRs and DC CSIs are the most commonly used circuits for large electric drives [14].

There are many technical and operational considerations involved in selecting the right type of converter. A few of the considerations are harmonics, for both the supply side and the load side, reliability, voltage levels, power levels, input frequency, output frequency range, the type of motor the converter will power, the speed of the motor and converter control. The question addressed in this work is the types of topologies that are available to be used with an electric propulsion and an IES and their adavantages and disadvantages.

First, the converter must be able to effectively transfer power from the generator to the propulsion motor. The converter must be compatible with supply voltage and frequency while meeting voltage and frequency requirements of the propulsion motor. The ship's design will determine the power required from the electric propulsion system. Power levels as high as 44MW (59,000HP) have been required for some installations of electric propulsion [11]. For high-power designs converters can be placed in parallel to reduce individual converter requirements. Additionally, multiple motors or double-wound motors can be used to achieve the required power per shaft if necessary.

For each topology the issues to be concerned with are the operation and physical construction of the converter. These include the range of output frequency, efficiency, reliability, controls, type of cooling and the effects of harmonics produced by the converter on the power supply and output. The actual operating range varies depending on the design of the entire propulsion system. Efficiency for a converter is based on the power electronic devices. The issue of reliability comes with two views. First, the issue of long-term reliability requires long mean time between failures. Second, the system must be able to continue to operate reliably in the presence of faults. Chapter VIII contains information on the control of converters. Considerable research has been conducted to minimize converter harmonics supplied to the motor and those imparted back to the power supply. The final section of Chapter VI is dedicated to effects

and reduction of harmonics with relationship to converters, electric propulsion and the IES. In Chapter VIII an investigation into the controls of the propulsion frequency converters will be analyzed. Control issues include ease of operation, ability to meet the performance specification and the complexity of controls.

3. Types of Converter Systems for Electric Propulsion

From the information already provided, the use of DC motors is not addressed due to the high propulsion powers required for the system and the well documented limitations of current DC motors [1,2]. There are three primary types of converter systems that fit the application listed above: AC-AC Cycloconverter, the AC-DC-AC Synchroconverter (current source inverter) and Pulse Width Modulated Voltage Source Inverter (PWM VSI) [11]. Figure 4-2 illustrates arrangements for the types of converters for electric propulsion.

The first type of converter to be addressed is the Pulse With Modulation (PWM) converter. This converter is considered a voltage source converter. It uses an AC VSR device to convert AC voltage to DC voltage and a DC VSI to convert from DC back to AC. Of the three types of converters the PWM uses the newest types of power electronic devices and is the most flexible type of converter [15]. An additional advantage, with a voltage source converter an inductive load can be accommodated, making induction motors as well as synchronous motors available for variable speed drives [15]. A further advantage stems from the ability to use different types of power electronics devices. The cycloconverter and the synchroconverter use thyristor devices with natural commutation while the PWM converter uses either GTO, or IGBT, with forced commutation [15]. As a consequence, the PWM converter may be used to "chop" the voltage waveform being impressed on the stator windings and thus control the fundamental amplitude [15]. This is where the name Pulse Width Modulation is derived.

There are currently drawbacks associated with applying PWM with very high power drives. First, the available voltage levels are limited by the electronic devices. As previously stated the IGBT device development is at a 2,500V maximum. Second, the power that can be used with the PWM converter is limited. These converters are used on many smaller applications from 5-8 MW with GTOs and 1 MW with IGBTs [11]. However, when voltage and power ratings increase for GTOs and IGBTs the use of the PWM

converters may become attractive. So based on the information provided on the current state of the technology, the PWM converters are excluded from further consideration for use in the electric propulsion system.

The current source converter or synchroconverter and the cycloconverter are both used in large marine propulsion designs including those above 10MW [11,14]. The synchroconverter is a well proven and reliable converter. The basic principle of operation has been known for over 50 years [14]. The combination of synchroconverter with synchronous motor drive has found a wide range of different uses in the power range between 1MW to 100 MW [15]. The basic module of a synchroconverter is the three-phase bridge rectifier which is known as a six-pulse arrangement. The current source converter or synchroconverter is considered an AC VSR device. An AC VSR device is used to convert AC to DC to provide a DC current. A DC CSI, which is the network analog to the AC VSR, is used to convert from DC back to AC. The DC link contains a large inductance to maintain a constant link current and emulate a constant current source. The DC link decouples the frequencies of the AC supply and the motor. Therefore, the motor speed is not limited by the source AC frequency. This allows the motor to operate at frequencies higher than the supply frequency.

Because the converter is externally commutated current source with a DC link, the output voltage is generated by the motor and impressed on the load commutated converter at the motor side. For this to work the synchronous motor must be fitted with damper windings. The damper windings reduce the commutating inductance and keep the duration of the load commutation short. Figure 5-3 illustrates a current source inverter powering a synchronous machine. The DC link contains a large inductance, L, that supplies a near constant current to the machine-side converter. The figure also shows the elements of the three-phase bridge rectifier.

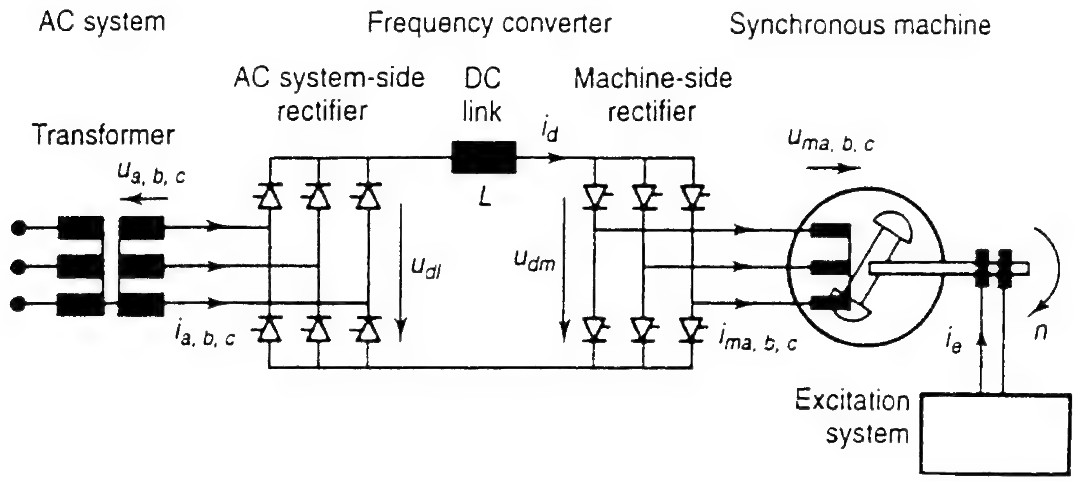

Figure 5-3. A general configuration for a current source frequency converter supplying a synchronous motor [14].

There are several advantages to using a synchroconverter. First, the synchroconverter uses thyristors as the switching device. This makes the controls for the converter simple because thyristors work on the natural commutation principle. Second, thyristors can readily accommodate the required power demands of a ship propulsion system. The choice of thyristors is necessary to allow for the absolute peak voltage conditions which can be experienced under normal, abnormal and fault conditions [11]. In high voltage DC transmission systems, externally commutated converters up to hundreds of kV and thousands of MW per system have been in commercial operation for many years [14]. The high power and voltage levels are reached by using the thyristors in series or by series connection of converters. Series connection has advantages compared to parallel connections. High-voltage, low-current systems reduce power losses in the converters, motors, transformers and cables [14]. By reducing the current a more cost efficient design can be realized. The third advantage to the synchroconverter is the fault-tolerances that can be designed into the system. When designing high-power systems the need for reliable and fault tolerant designs are very important. As previously stated high-power designs use thryristors and/or converter units in series. When thyristors fail they appear as a short circuit. Thus, several thyristors in series can enable the converter to survive device failures. Some converter units are built with up to 133%

of the required amount of electronic devices to ensure reliable operation [11]. This also allows a fault to be isolated and allows the unit to continue operation when the fault occurs. Converter units themselves may be of higher rating than required to accommodate the loss of one unit when operating in series. Further, since the synchroconverter is a current-controlled device, the current is naturally regulated so that over-current protection is inherently provided. The use of extra components or de-rating of a synchroconverter adds a margin of reliability and safety of operation, even though the normal operation of the synchroconverter provides for fault tolerance. The fourth reason for using a synchroconverter is the ability to reduce the amount of harmonics produced by the converter to a low level. To achieve the lowest possible line-side harmonics, the synchroconverter uses a 12-pulse configuration. The 12-pulse configuration will produce currents closer to a sinusoidal shape than a six-pulse configuration [14].

For 12-pulse operation, two 6-pulse converter bridges are connected in series, each fed by separate secondary windings from a transformer. The primary side or source side is wye connected, while the secondary side or load side consists of one wye and one delta connection [14]. The synchronous motor is equipped with two three-phase windings with a 30° phase-shift on the stator . The reason for the transformer with two sets of winding is to displace one three phase current by 30° from the other. The wye-to-delta connection would displace the incoming voltage by 30°. The current phase shifted converter would then be connected to the second set of motor windings with a 30° phase shifted position on the stator from the other winding. The current fed in each of the three-phase windings remains a six-pulse current. The resulting magnetic field which penetrates the motor has 12-pulse dominant harmonics. This reduces the torque ripple and the rotor temperature rise caused by the losses associated with induced current harmonics in the rotor and its damper windings [14]. Figure 5-4 shows the layout for a 12-pulse synchroconverter and the general pulse steps that are offset by 30°.

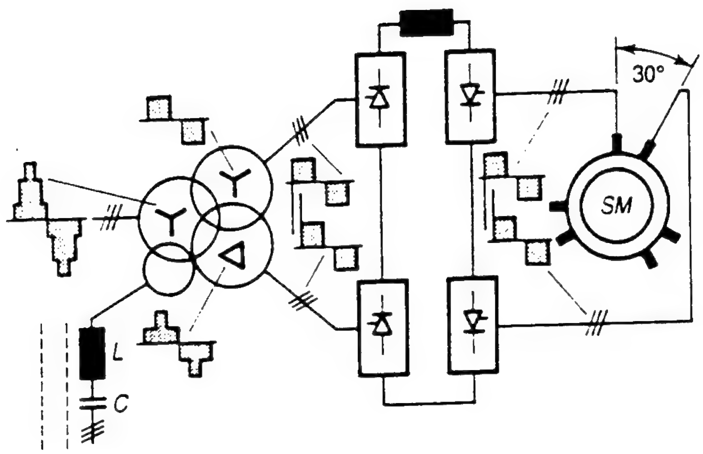

Figure 5-4. Series connection of two six-pulse bridges to form a 12-pulse configuration [14].

The first and one of the most noted uses of a synchroconverter in electric propulsion was in the passenger ship *Queen Elizabeth II* (*QE II*). The *QE II* was converted from a direct drive steam ship to a diesel-powered electric drive ship [7]. There are two synchroconverter drives used on the *QE II;* each unit is rated at 11.5MW and is fed directly from the ship's main propulsion bus at 10 kV. The thyristor used in the synchroconverter for the *QE II* is rated at 3,600V and 1,278A [11]. Each branch of the converter is fitted with 12 thyristors. A significant margin of safety has been incorporated in the design given that the unit can continue to operate with four of the twelve thyristors in one branch being short circuited. More protection is achieved because the thyristors are de-rated, operating at a lower current than their designed current rating. The rated DC link current is 1,047A and each device can operate at 1,278A. Extra safety is added by the incorporating surge suppression circuits on the supply and load side of the converter. Figure 5-5 is a simple representation for the supply and motor converter showing the 12-devices per branch and surge protection circuits for the *QE II* converter units.

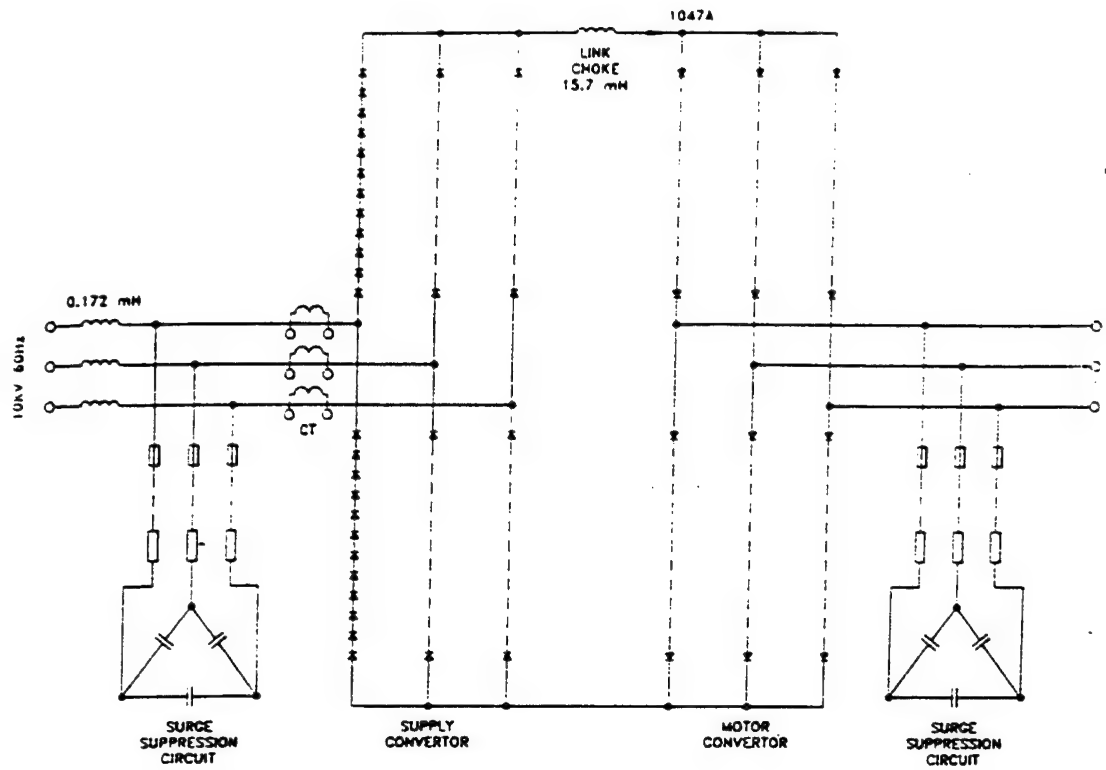

Figure 5-5. Electrical power circuit for *QE II* synchroconverter [11].

The final type of converter under consideration is the cycloconverter. The cycloconverter in conjunction with the synchronous motor was put into use in the 1960's. It was the first of the large electric drives to take advantage of power electronics technology [14]. With few changes in fundamental operation, the cycloconverter is still a leader in electric drives. The cycloconverter is considered an AC VSR. One of the most notable difference between the cycloconverter and the PWM or synchroconverter is that it does not use a DC link between the supply and the load side of the converter. The cycloconverter only uses the AC VSR topology and unlike the synchroconverter there is no DC CSI inverter on the load side. Cycloconverters for large drives are made up of line-commutated controlled six-pulse rectifier bridges, whose output is sinusoidally controlled . The cycloconverter uses two anti-parallel bridges components per phase for a total of six bridges for a three-phase system. Each phase has one bridge for each direction of the generated AC current The bridge units take each phase of the AC supply and cuts

individual sections out of the AC supply voltage for recombination at a new frequency. The general design of a cycloconverter has a transformer on the AC supply side with three separate secondary sides. The transformer is used to decouple the commutation loops of the three phases of the supply voltage. Since the voltage consists of sections of the AC supply voltage its frequency is limited to about 40% of the supply frequency.

As with the synchroconverter, the cycloconverter is traditionally used with a synchronous motor. However, the cycloconverter can be used with induction motors and in slip energy recovery systems. When using the synchronous motor together with the cycloconverter there are several differences between the operation and design of the motor as compared to the synchroconverter. First, the cycloconverter generates a voltage, not a current, which is impressed onto the stator windings. Because the damper windings would reduce the leakage inductance and hence the filtering effect, the motor must be built without damper windings to ensure as sinusoidal as possible stator currents [15]. This leakage inductance is one of two elements that couple the stator and rotor currents to cause motion. Figure 5-6 represents a typical cycloconverter drive using a synchronous motor with external rotor excitation system.

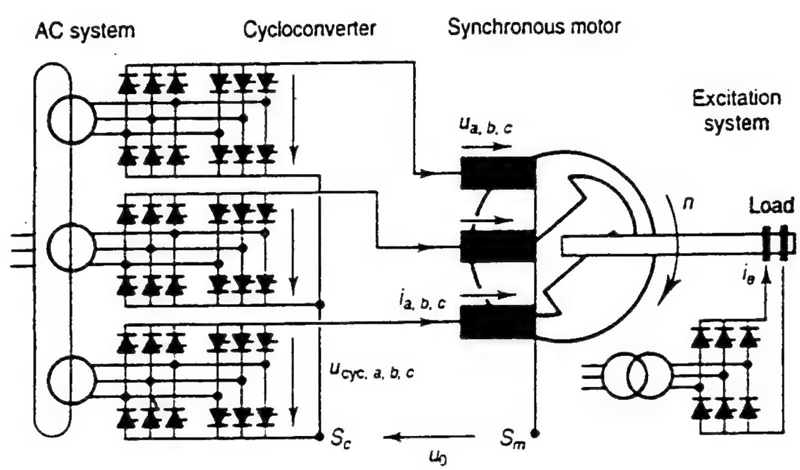

Figure 5-6. Cycloconverter-fed synchronous motor [14].

A cycloconverter control system is more involved than the comparable synchroconverter system. The main objective is to control speed by adjusting the synchronous motor torque. Speed control is typically realized while maintaining rated stator flux.

The general ideas addressed with the synchroconverter in terms of being able to reduce harmonics, provide redundancy and de-rating components for reliable operation can be applied to the cycloconverter. There are four items that make the cycloconverter different than the synchroconverter. First, variable frequency cycloconverters produce less total harmonic distortion than the synchroconverter [6,14]. The cycloconverter produces variable inter-harmonics at the AC side. These harmonics must be removed with active filters if required. Second, when feeding two different sets of windings with a 12-pulse synchroconverter, the windings must be spatially displaced by 30°. When feeding separate winding sets with separate cycloconverters, the winding systems have to be decoupled magnetically to such an extent that their voltages do not produce high interacting current harmonics. Third, the six-pulse cycloconverter normally uses a transformer to decouple the commutation loops of the three single-phase cycloconverters; however, a transformer is not always required. The converter may supply the three phases of the motor independently. Harmonic distortion reduction can be facilitated by connecting the motor windings in a wye connection. The last difference is the cycloconverter does not have a DC link that decouples frequency. A cycloconverter can only have an output frequency that is 40% of the input frequency [14]. This must be considered when designing the AC supply components and the synchronous motor. Figure 5-7 illustrates two six-pulse cycloconverters supplying two separate winding sets of the same motor.

A cycloconverter design was used in the U. S. Coast Guard ice breaker *Healy* launched in 1997. The *Healy* uses two variable-speed propulsion drive systems. The systems are fed from the ships 6.6kV main propulsion bus. Each system use two cycloconverters in series from three individual three phase 2.9MVA transformers. One is a wye-to-wye connection and the other is a delta-to-delta connection. This results in a 12-pulse cycloconverter design similar to the 12-pulse synchroconverter design. The output to each converter feeds a separate winding in a synchronous motor. The motors are rated for 11.2 MW at 130 rpm. Figure 5-7 depicts the electric propulsion converter and synchronous motor on the *USCG Healy*.

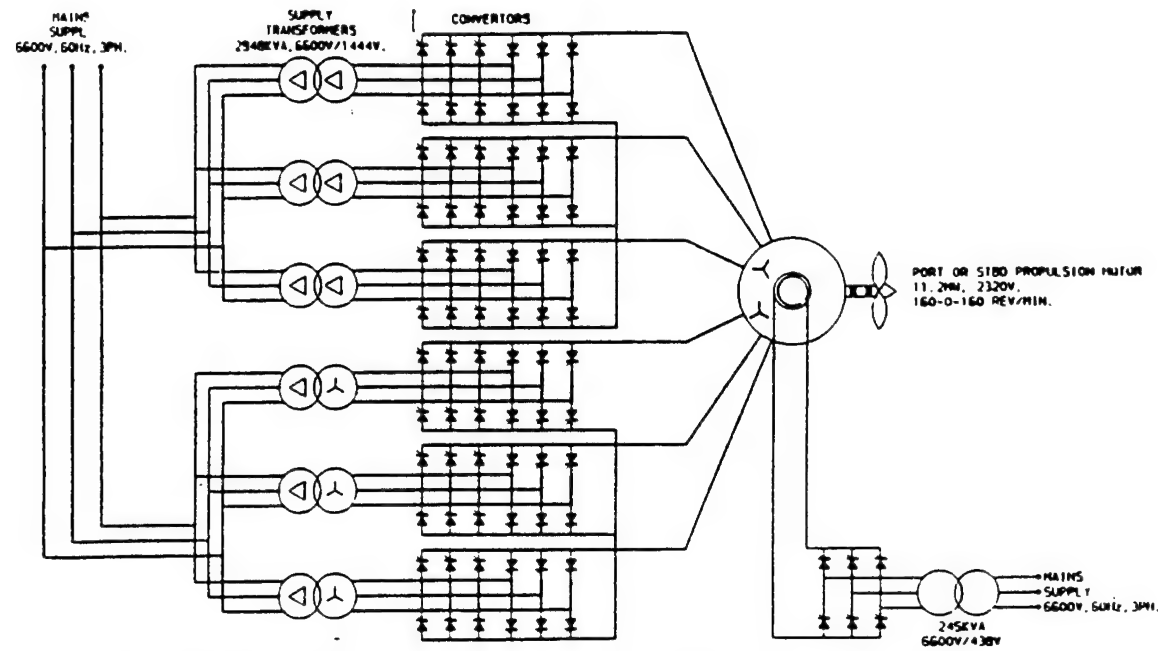

Figure 5-7. The cycloconverter circuit arrangement for 12-pulse operation [11].

There are two interesting differences between the *QE II* and *Healy* designs. First, the *Healy's* cycloconverter has only one power electronic device per bridge per phase in any direction. If one of these devices fail then that converter is lost. Whereas the *QE II 's* synchroconverter has numerous redundant power electronic device per phase. The second issue is that the *Healy* employs a 12-pulse cycloconverter system and the *QE II 's* uses only a six-pulse synchroconverter system. The reduction of harmonics to the shaft to minimize radiant noise for the *QE II* was not considered a critical issue; however, harmonics to the shaft are very important to a surface combatant. A combatant is designed to transmit as little noise as possible into the water to avoid revealing its present to underwater listening devices and submarines.

Even when considering the type of converter to use there are additional design features to be reviewed and analyzed. For shipboard use the issue of space and weight are always a concern. When looking at converters the space that each unit takes up is proportional to the power output. This is driven by three factors. First, higher voltage and power requirements result in larger electronic devices. Second, the more power transferred will result in more heat that must be removed from the converter. There are normally two ways to remove heat from a converter: air or liquid cooling. In most high-power marine installations, liquid cooling is the preferred method due to the availability of sea water. Further a liquid-cooled converter is normally smaller and lighter than the air-cooled units. However, there is a reliability,

space and weight trade-off between water and air-cooled units when one considers the use of heat exchangers and pumps to move the cooling water.

D. ANALYSIS OF THE PROPULSION MOTORS

1. Design Considerations

The final item to review for the electric propulsion system is the motor. When selecting a propulsion motor the following must be considered : size (length and diameter), weight, efficiency, noise signature, magnetic signature, shock capability, reliability, maintenance, cost and compatibility with converter topologies [16]. The current designs for electric motors for marine propulsion are larger and heavier than their counterpart the reduction gear in direct drive systems. Currently a number of countries are developing and building smaller, lighter and more efficient electric motors for marine propulsion [17].

2. Types of Electric Propulsion Motors Currently Available

In Chapter IV, it was explained that there were several different motors being used or under development for electric propulsion. There are two principle motors for use with electric propulsion at the power levels required by a surface combatant: the induction motor and the synchronous motor. With regards to the synchronous motor there are two types: the field wound and the permanent magnet.

The converter fed induction motor is well proven for large variable speed drives. The induction machine may have numerous phases; however, the most common number of phases is three. The induction machine requires excitation to be supplied to only the stator. The rotor windings are excited by induction from the rotating magnetic field set up by the stator winding current [13]. Of all the different types of electric machines the induction motor is the most common [13].

The induction motor has both advantages and disadvantages when being used for electric drives. The first advantage to the induction machine is that it is easy to build and costs less compared to other motors. The induction motor does not require a magnetic field to be established on the rotor from outside the machine or from permanent magnets mounted on the rotor. This reduces the cost of manufacturing the rotor and the cost in providing a system to deliver DC power to the rotor (or the cost of permanent

magnets). Second, the induction motor provides robust operation with low maintenance requirements. Without the need for any externally derived magnetic field on the rotor, maintenance on the rotor is not required. The induction motor is also mechanically rugged which provides a long service life over other motor designs [16]. The induction machine does have a number of disadvantages: volume to power out is larger than other motors, a lagging power factor is required and the efficiency is less than that of the synchronous machine [16]. The induction motor can be used with a cycloconverter or a pulse-width-modulation converter. That is, since it can only operate at a lagging power factor, a naturally commutated current source inverter is not an option.

The next type of motor to be considered is the field-wound synchronous motor. The field-wound synchronous motor is the most frequently used motor for marine electric drives. In terms of power being supplied to the motor, the field-wound synchronous motor is a doubly supplied machine. In the stator, there are uniformly distributed polyphase windings similar to that found in the induction machine. The stator is excited by AC being supplied by the frequency converter, like the induction machine. However, the rotor is also excited by a DC source through slip rings mounted on the rotor or via a rotor-mounted excitation system. The rotor windings produce the magnetic field that locks the rotating electrical field of the stator with the rotor. Synchronous motors can be built with a second set of short-circuited rotor windings called damper windings. The damper windings are provided for two reasons. First, when starting the motor the windings produce a magnetic field when acted on by the flux of the stator that couples the rotor with the rotating field of the stator. This emulates the basic operation of the induction motor. The second reason is that the damper windings provide a damping effect which tends to restore nominal operation when the system is disturbed. It should be noted when using a cycloconverter with a synchronous motor, damping windings are not fitted on the rotor.

There are advantages and disadvantages to the field-wound rotor synchronous motor. The synchronous motor and the induction motor have the common disadvantage in having low power density; however, the size for an field-wound synchronous motor is less than an induction motor for the same horsepower. As stated at the introduction to this section, the size of the electric motor is the largest disadvantage to electric propulsion. There are several reasons for the continued domination of

synchronous machines in electric propulsion designs. One advantage is that the synchronous motor can operate at unity power factor or at a slightly leading power factor. Another advantage is a high low-speed torque capability. Also, because a magnetic field is produced on the rotor, the required air gap for a synchronous motor can be larger, improving shock and vibration performance compared to an induction motor. The larger air gap allows the rotor to move inside the stator without the two making contact. This reduces the chance of damage to the rotor or stator. The synchronous motor can be used with all three types of major converters used today: the synchroconverter, the cycloconverter and the pulse-width-modulation converter. The synchronous motor and synchroconverter combination affords a much greater range of motor speeds than cycloconverters, but the combination also produces increased current and torque harmonics.

3. Types of Propulsion Motors Under Development

The two types of motors listed above are both readily available and have proven performance records. The next part of this section is to review the motors that are currently being studied for use with electric propulsion. These motors are the permanent magnet synchronous motor, the transverse flux motor, the switched reluctance motor and the DC homo-polar motor.

The permanent magnet synchronous machine, as the name suggests, operates like a synchronous motor. The permanent magnets replace the wound rotor and the need for external excitation. The motor is still under development for large power units greater than 500kW. The permanent magnet machine is the most optimum motor for electric drives. The advantages to the permanent magnet synchronous motor are numerous. The first advantage is that no external rotor excitation power supply is required. The second advantage is that rotor iron and copper losses are eliminated improving efficiency. The third advantage is that theoretically the motor can be made much smaller and lighter than the wound-rotor synchronous and induction machines. With all these advantages there are some very sizable disadvantages in producing a synchronous motor that competes with the induction and wound-rotor synchronous motors. The first disadvantage is the cost and availability of the rare earth metals for the rotor magnets. The second disadvantage is an increased number of poles for an effective design. There are typically 4 to 5 times as

many poles per unit circumference required [17]. The large pole number of the permanent magnet motor means that it has a greatly reduced thickness of stator core and rotor shell. The permanent magnet machine can be combined with the same converters as the wound-rotor synchronous motor. The increase in the number of poles required for a permanent magnet motor must be considered in determining converter operation and speed of the rotor. In the case of a 60Hz system supplying a converter for a 60-pole permanent magnet motor, the supply frequency for the motor to rotate at 180 rpm would be 90Hz. Because the cycloconverter can supply a maximum output frequency of 40% of its input frequency, a cycloconverter can not be used with an input frequency less than 225Hz.

The next type of motor is called the Transverse Flux Motor (TFM). The TFM is a special form of permanent magnet synchronous motor. Figure 4-3 represents the simplest form of a TFM. The new design is an attempt to increase the efficiency and power density of the permanent magnet motor. Transverse flux motors have been constructed up to 200kW and advanced designs have motors operating in the 16 MW to 20 MW range [12]. The major difference is the design of the stator and rotor and physical arrangement with relationship to one another. The TFM uses permanent magnets mounted on discs where each disc is flanged to a rotor drum [18]. The permanent magnets are bonded to the rotor and are circumferentially magnetized to achieve a high air-gap flux density using the principle of flux concentration [12]. The magnets are arranged to have alternating flux fields. The stator of the TFM has a number of solenoidal armature coils. Each armature coil is associated with one set of permanent magnets located on the disc. The alternating flux from the permanent magnets is carried by stator cores, which are "C" shaped and form a flux linkage with the respective armature coil [18]. Each pair of permanent magnets with its associated armature coils and stator cores forms a separate phase of the motor, with the two coils of one phase being connected so the current flows in the opposite directions around the machine [12].

The TFM operating principles are the same as the permanent magnet machine and has some of the same advantages and disadvantages as the permanent magnet synchronous motor. One advantage unique to the TFM is an increase in power density. The points that work to increase the efficiency and power densities are that the magnets are arranged in a flux concentrating configuration to maximize flux to the stator. Both sides of the rotor are active and contribute to the production of torque and the stator coil is

relatively unconstrained by the arrangement of the armature. A unique disadvantage to the transverse flux motor is the difficulty in construction due to multiple rotors on the same shaft and the position of the numerous armatures located around and between each rotor [12]. Various designs are being studied to reduce the construction time and effort.

The final two motor types are the Switched Reluctance Motor (SRM) and the homo-polar motor. The SRM is the newest attempt to increase efficiency and power density. This motor by far is the most novel in comparison to other electric motors. The motor is still in the early developmental stages. The SRM has no magnets or windings on the rotor. The production of torque is accomplished by exciting the stator winding in a predetermined sequence which attracts alternate rotor poles by bringing them into alignment with the excited poles of the stator. The advantages and disadvantage compare similarly to the induction machine.

The last motor type is the homo-polar motor. The homo-polar electric motor is a true DC machine. Previous configurations of propulsion systems using current DC motors could not produce the power required. However, the homo-polar motor has the possibility of overcoming the power limitations of DC motors. The basic operating principles of a homo-polar motor are easily explained by referring to Figure 5-8. The magnetic field in this homo-polar is purely radial. The magnetic field is intercepted by a drum of copper which has current passing along its axial length. The Lorentz force interaction between the magnetic field and the current in the drum develops a force on the drum causing rotation [1].

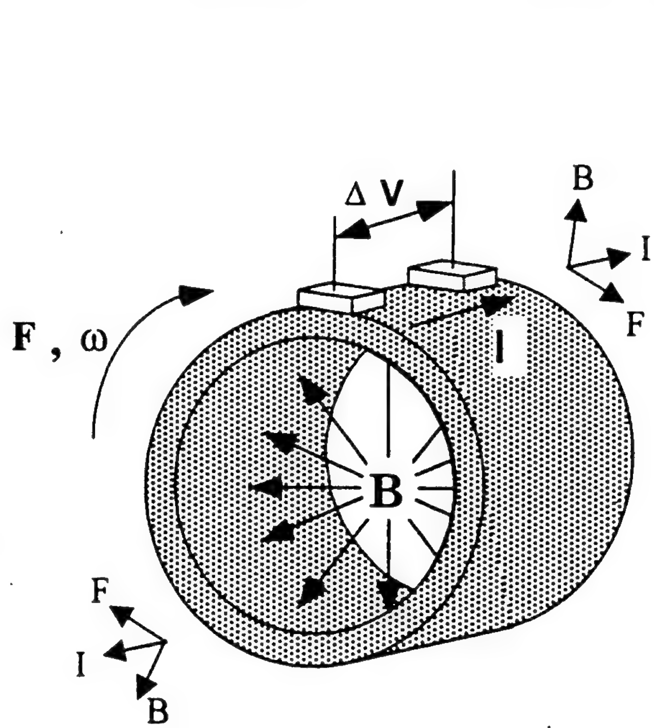

Figure 5-8. Schematic of a homo-polar motor concept in the drum configuration [1].

The motor uses superconducting permanent magnets to produce the uniform magnetic field. The homo-polar motor has two advantages: elimination of harmonics and torque pulsations and very high efficiencies (~ 99%) [1]. Further, the homo-polar motor can operate over a wide range of operating voltages and currents making optimization with other equipment easy [1]. The disadvantages to the homo-polar motor are the contacts from the motor to the power supply and the cooling of the superconducting permanent magnets [1].

VI. ANALYSIS OF THE INTERGRATED ELECTRICAL SYSTEM AND HARMONICS

This chapter covers the remaining systems that will make up the Integrated Electrical System (IES). In the next section of this chapter, the ship's service electrical system is analyzed with regards to the ship's service generator and the integration of the ship's service electrical system using various architectures. The third section of this chapter introduces major electrical loads, other than main propulsion and ship's service electrical, that will be part of the IES. These major electrical loads are termed auxiliary loads. The final section is a discussion on harmonics in the electric propulsion system and the IES. The issues that are covered include: where the harmonics are produced, why harmonics are a concern and the ways harmonics are reduced.

A. ANALYSIS OF THE SHIP SERVICE ELECTRICAL SYSTEM

1. Issues for Supplying the Ship's Service Electrical System

This section is divided into two parts: ship's service electrical generators (SSEG) and ship's service operation with the IES. An analysis of the ship's service electrical generators and design issues with the prime mover and generators are reviewed. The ship's service electrical system (SSES) is analyzed with respect to compatibility, distribution architectures and operational requirements with the IES.

2. Ship's Service Electrical Generators

In an IES the main propulsion generators can provide power for both propulsion and for all other ship's electrical loads. There will be periods when the propulsion generator capacity will significantly exceed the requirements of the ship's electrical load and when the combined ship's load and propulsion load will exceed the capacity of a single propulsion generator. Examples of the former occur when the ship is pier side and shore power is not available or when the ship is at anchor. In these cases the use of a smaller prime mover and generator for the SSES would be economical. During normal operation the SSEG could provide power to the main bus alleviating the need of operating another propulsion generator. Still another example is best illustrated by first assuming that one propulsion generator can provide for propulsion power at a maximum speed of 20 knots and a ship's service electrical load of

1,800kW. Now if a speed of 22 knots is required, the smaller capacity SSEG could be used to provide the extra power without operating a second main propulsion generator. This feature would be more economical than running a second main propulsion generator with very little load.

There are several other reasons to provide SSEGs in addition to the main propulsion generators. First, if all main propulsion generators are out of service, there will still be available sources of power for auxiliary propulsion. The SSEGs can be located and connected to the vital loads to provide emergency power, thus isolating the loads from the IES. The use of a ship's service generator provides a degree of redundancy and more prime movers and power to the IES without large propulsion generators. These generators can improve safety of the ship if located in isolated protected parts of the ship while providing power for vital equipment.

There are several issues that drive the number and capacity of ship's service generators. First, a single ship's service generator should have the minimum capacity to support the ship's service electrical load while at anchor or pier side. The next issue is the maximum capacity for the ship's service generators. This factor is determined by the requirements of the IES and the ship. For example if the ship is required to have auxiliary propulsion using only SSEGs, then the load requirements of the auxiliary propulsion and the SSES will dictate the overall capacity and set the number of SSEGs needed. Also, the capacity of the SSEGs when operating with a propulsion generator should be considered when designing the IES. The final issues are redundancy and the extra capacity of the ship's service generators. Operational, economic and safety issues dictate the redundancy and extra capacity of equipment. The decision on the amount of redundancy and extra capacity is addressed by the ship's designer.

The SSEG's operating characteristics must match that of the electric propulsion system and the IES. If at any time the ship's service generator is to be operated in parallel with a main propulsion generator, then both generators must have the same output voltage amplitudes and frequencies and the same number of phases. For example when using a three-phase main propulsion generator with an output of 6.6 kV at 120Hz, the ship's service generator must match these operating characteristics.

The same issues that apply to main propulsion generators also apply to the SSEG when determining prime mover and generator design characteristics. Some of the issues for the SSEG prime

mover are efficiency, method of coupling prime mover and generator, space, cost and manning. With regards to the generator, power density and efficiency are major issues. It should be noted that the smaller capacity generators can use the new design technologies that are only available to produce power in the thousands of kilowatts range.

B. ANALYSIS OF THE INTEGRATED ELECTRICAL SYSTEM SUPPORT OF THE SHIP'S SERVICE ELECTRICAL SYSTEM

1. Issues of operation with IES and the Ship's Service Electrical System

One of the attractions to the IES is the ability to supply the SSES from the electric propulsion system. However, there are several issues that must be addressed. The first issue involves being able to supply power to two systems from a common source. The first option is to have the propulsion system and SSES have common operating characteristics. The second option is to have a method to de-couple the two systems, allowing each to operate with different characteristics. Second, harmonics introduced in either system must not be prohibitive and, of course, stability must be maintained for all possible operating conditions. The third issue involves fault detection, component protection and guaranteeing continuity of power to critical systems.

2. Ship's Service Electrical Distribution and IES Compatibility

The first issue, transferring power, from the main propulsion bus to the SSES, is one of compatibility. There are several different types of distribution for the SSES. The most common used today are 450V AC, three-phase, 50Hz or 60Hz distribution architecture. These systems are currently used for both direct drive ships and ships employing electric propulsion. Both direct drive and electric propulsion employ technology and components common with land-based electrical distribution systems. For direct drive ships, the SSES is fed from generators with matching characteristics. For IES the electrical propulsion system characteristics may not match the requirements for the SSES. In current electric propulsion systems the largest difference has been in terms of voltage. For example, the propulsion

generators may deliver 6.6kV three-phase and the SSES may require 450V. This voltage difference is currently facilitated by using large transformers to reduce the voltage.

There are several disadvantages to the 450V, three-phase, 50Hz or 60 Hz systems when using it aboard ship. One disadvantage is that the three-phase system requires independent wires for each phase. This increases the space, weight and cost of the electrical distribution system. Another disadvantage is that any time there is a need for a different frequency, a different voltage amplitude or DC voltage, there needs to be frequency converters, transformers or rectifiers. This again increases the space, weight and cost of the electrical distribution system. In a direct drive ship where the ship's service generators would operate in parallel with one another, redundancy is ensured by numerous switchboards and control devices that allow different sources of power to supply a single point. The IES has the additional disadvantage of requiring large step down transformers that must connect the main propulsion bus to supply the SSES at various points. This increases the number of transformers required. The frequency of the SSES when fed from the main propulsion bus frequency through step-down transformers. The only way this can be avoided is to use frequency converters connected to the main propulsion switchboard to feed the SSES [6]. Also, when SSES is fed directly from the main propulsion bus, harmonics produced by the propulsion motor frequency converters can adversely effect the SSES. These harmonics must be minimized by filters or they could damage sensitive components in the SSES [6].

A second type of distribution system under development is the DC Zonal Electric Distribution System (DC ZEDS). DC ZEDS is being developed for the U.S. Navy at its Naval Surface Warfare Center (NSWC), Carderock , MD and employs port and starboard DC voltage buses with the electrical distribution system being divided into numerous zones [19].

In DC ZEDS, the AC power supplied by the main bus is rectified and regulated for distribution. The number and type of rectifiers would depend on the number of points that AC would be available, the efficiency of the rectifiers, the requirements of the ship's service electrical load and the amount of redundancy required. The rectifiers are phase controlled and are used to regulate the bus DC voltages. The rectifiers will also have filters to reduce the harmonics produced by the main propulsion frequency converters on the AC supply. By employing-high speed electronic controls and redundant rectifiers, a fault

with or failure of a rectifier will not effect the SSES [19]. The DC power from the rectifiers is provided to two buses, a port bus and a starboard bus, that run the length of the ship. These buses would be arranged so that they are protected from damage and located away from one another for added survivability. Both buses can provide power to any zone with the capacity to support the entire zone's electrical load from one bus. The buses has the ability to be cross-connected to allow transfer of power from one bus to another in the event of one bus being damaged [19].

In each zone DC-to-DC converters are supplied power from the DC buses and regulate the voltage level for distribution inside the zone. The DC-to-DC converter is called a Ship-Service Converter Module (SSCM) [19]. The SSCM perform three main functions: connection point for either DC bus to supply power to the zone, DC voltage regulation from the DC bus to the distribution system and minimizes the effects of load changes in the zone or on the bus from adversely effecting one another. From the SSCMs the power is distributed inside each zone. The distributed power is supplied to Ship-Service Inverter Modules (SSIM) and DC-to-DC converters located inside the each zone [19]. The SSIMs and DC-to-DC converters allow changes to the DC voltage being distributed inside the zone for use by individual components. The SSIM changes the distributed power from DC-to-AC with varying voltage amplitude and frequencies for components requiring AC power. The DC-to-DC converters change distributed DC voltage to levels to be used by components requiring DC voltage. For example, the types of power that may be needed in one zone are three-phase 450V at 60Hz; single-phase, 120V at 60Hz; three-phase 220V at 400Hz and 110V DC. All of these different types of power are provided by the SSIM's and DC-to-DC converters being fed by DC distribution inside each zone.

There are several issues involved with using SSIM's and DC-to-DC converters in each zone. First, they provide fault detection and isolation for components. Second, because the type of power can be customized for each component, the power type no longer is a limiting factor in component operation. This allows for optimization of machine and electronic component designs. If an SSIM is dedicated to supply an individual motor, that SSIM can serve as a variable speed controller and provide the circuit protection for the motor. The SSIMs eliminate the need for separate circuit breakers, controllers and fault protection which are used today. Also, the SSIM and DC-to-DC converters can be assembled using the

same components allowing commonality between ship classes and reducing the stocking of different types of spare parts [19].

The DC ZEDS has two principles that make it attractive for shipboard use and one principle that makes its use compatible with the IES. The first principle is the use of a zonal design.

A zonal design reduces the need for longitudinal cable runs. This enhances producibility, decreases cost and reduces weight. With two sources of electrical power for all zones, distribution to components is maintained in the case of bus damage. The second principle is the us of DC instead of AC for system architecture, construction and operation. Solid-state conversion to DC enables rapid and simplified current limiting and fault protection. The use of DC reduces the number of main power cables increasing survivability, while decreasing weight and cost. There is a reduced number of load centers for DC distribution. The DC system does not require synchronizing equipment to parallel power sources. The circuit protection devices in a DC system are solid state which improves fault isolation, increases reaction time and allows faster response [19]. As previously introduced, DC distribution also allows the conversion to AC with different frequencies and voltages at the point of use which allows optimization of size and cost of electrical components [19].

DC ZEDS is attractive for use with electric propulsion because of the inherent decoupling of the main propulsion bus, frequency and voltage, with that being used by the SSES. The main propulsion bus is not limited to frequencies that also have to support the ship's service electrical distribution system. The voltage level of the DC buses can be independent of the propulsion generators through the use of power electronic rectifiers.

Even though there are numerous advantages to the DC ZEDS, there are disadvantages as well. The major disadvantage is the stability of the DC ZEDS two main buses. The primary stability issue results from the interconnection of tightly-regulated (high-bandwidth) power converters, a source and various passive filters [19]. The DC-to-DC converters exhibit a constant-power characteristic that manifests itself as a negative input impedance over a certain frequency range. This negative impedance could under certain operating conditions or parameters result in sustained oscillation or outright instability.

The problem is that the system must be designed so that it remains stable for all possible configurations and that excessive filtering (capacitors and inductors) is not required.

Figure 6-1 represents the layout for a conventional AC distribution verses a DC ZEDS layout for a surface combatant. The figures show only the SSEG providing power to the SSES.

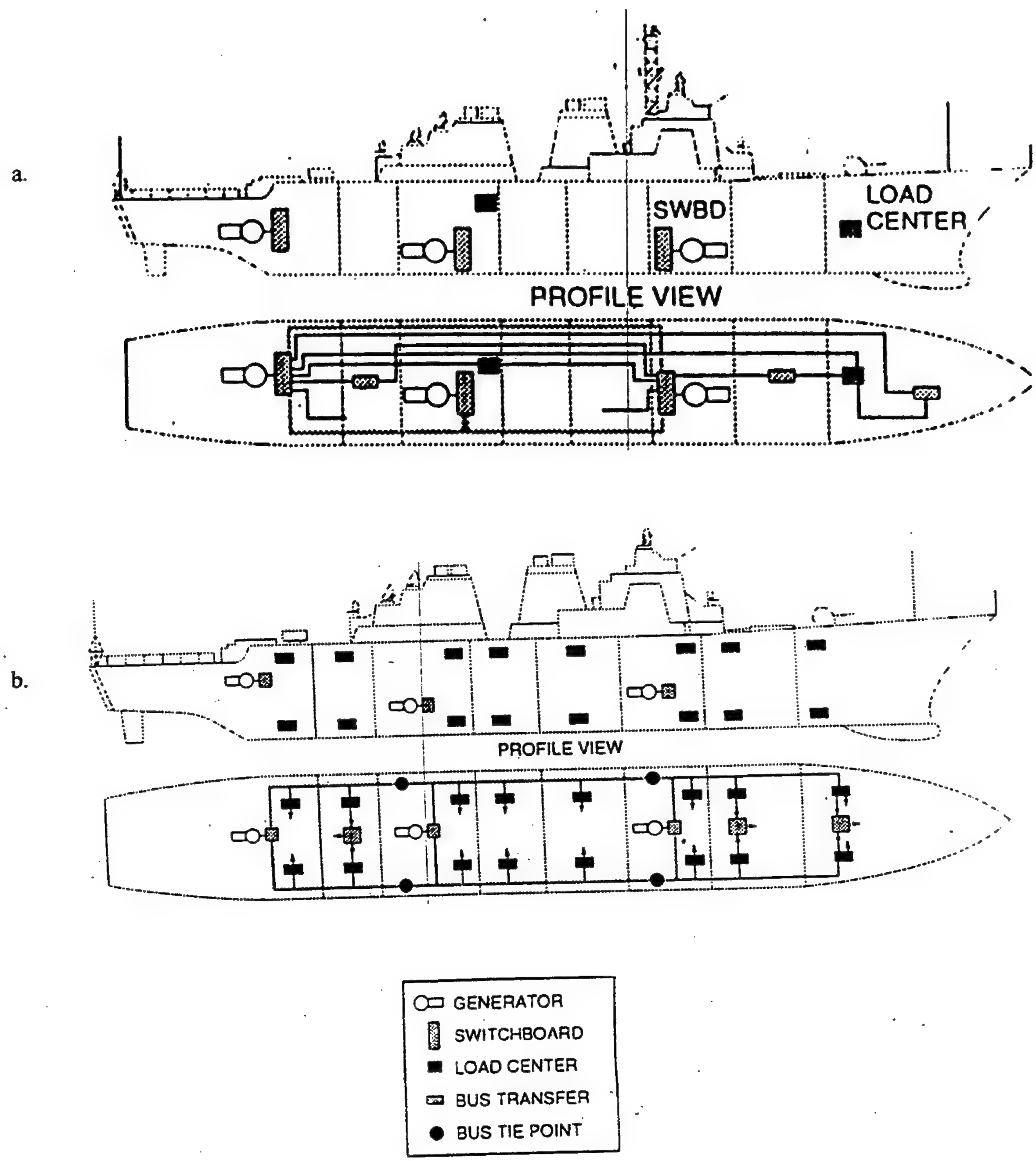

Figure 6-1. Comparison of (a) conventional AC verses (b) DC ZEDS layout for SSES [19].

C. SHIP'S AUXILIARY LOADS UTILIZING INTEGRATED ELECTRICAL SYSTEM

1. Types of Auxiliary Loads

With the IES design the two major users are main propulsion and the SSES; however, these are not the only ship's systems that can derive benefits. One of the subsidiary objectives of the IES is to provide power to various auxiliary loads from common power sources. On a typical warship using direct drive propulsion, prime movers are dedicated to propulsion and full power is required only an estimated 10% of the time a ship is underway [5]. In another situation, ships with dedicated ship's service generators may require electrical power for short periods of time greater than the standard ship's service electrical load or require other forms of energy for operation. Two examples of such electrical loads in commercial ships include electric cargo pumps in self off-loading tankers and electric cargo handling equipment for bulk cargo ships. These added electrical loads may only be used for short periods of time in the life of a ship, but a ship must have the power producing capacity installed to support these peak demands. For warships there are similar demands to provide capability to support ship operations. In some cases the form of energy required may not be electrical. An example of energy demand other than in the form of electricity is the steam catapults of a modern aircraft carrier.

There are many auxiliary loads that can be used with the IES. As previously stated cargo handling equipment is the major auxiliary load on commercial ships. A warship typically has different auxiliary loads as compared to commercial ships. For a warship using IES there are three major auxiliary loads proposed: maneuvering thrusters, Electro-Magnetic Aircraft Launching Systems (EMALS) and Pulse Energy Weapons (PEW). While the PEW and EMALS are still under development their use will require that a ship have the ability to produce large amounts of electrical power.

This section introduces some of the major auxiliary loads that can be supported by IES. For each auxiliary load a brief description of its operation and design is presented.

2. Operation and Designs of Maneuvering Thrusters

An auxiliary system that can be powered from the IES is the maneuvering thruster. The maneuvering thruster can fill the role of bow or stern thruster or Auxiliary Propulsion Unit (APU) in the

event of a total main propulsion failure. Currently these systems are powered directly from a prime mover or from the ship's service electrical system. In the case of the system being power directly from a prime mover, the maneuvering thruster is driven via gears and shafting. The ability to change the direction of the thruster is achieved with reversing gears or controllable pitch propellers. With reversing gears the amount of thrust is controlled by the speed of the prime mover. With controllable pitch the amount of thrust is controlled by the pitch of the propellers. The operation and use of controllable and variable pitch propellers are addressed in Chapter VII. When maneuvering thruster designs utilize a dedicated prime mover, the additional prime mover adds increased maintenance, cost, space and fuel consumption. An example where a prime mover drives the maneuvering thruster is on the U. S. Navy's General Purpose Assault Ship, LHA-1 class. The diesel engine drives a shaft and gear system that powers the propeller. The direction and amount of thrust is achieved by a controllable pitch propeller. (Note: The same diesel engine can also drive an emergency generator. When the bow thruster is in operation the generator will not be fully loaded.)

The electric powered maneuvering thrusters require that additional electrical capacity be installed in the ship to account for their operation. Two examples where electric maneuvering thrusters or APUs are used is the steam turbine driven cargo ship of the Gulf Pacer Class and the U.S. Navy Guided Missile Frigate, FFG-7 Class. The Gulf Pacer Class requires that an additional ship's service turbine generator be dedicated to the maneuvering thruster. If one of the two installed ship's service turbine generator was unavailable, the ship would be unable to use the maneuvering thruster. In the case of the U.S. Navy frigate, power for the APU is supplied from the SSES when operating three of its four SSEG. The APU is also the backup source of propulsion in the case of damage to the ship's one shaft, damage to the reduction gear or the failure of both main propulsion gas turbines. For the Gulf Pacer Class of cargo ship the maneuvering thruster requires 750kW (1,000HP). With the rating of each generator being 1000kW it was necessary to dedicate one generator to the maneuvering thruster. On the U. S. Navy frigate the APU is rated at 970kW (1,300HP). With the normal ship's service requiring two of the 1000kW generators to be in operation, a third generator must be operating to support the APU.

For today's maneuvering systems, the most common design is the use of constant speed motors that drive a controllable pitch propeller. The system is normally supplied from a dedicated prime mover/generator set or from the ship's service distribution system. The IES would be able to power the maneuvering thruster directly from the main propulsion bus. When designing the system, two things must be considered: the supply from the main propulsion bus and the maneuvering thruster power requirements. For example if the main propulsion bus was rated at 6.6kV, three-phase at 60Hz the maneuvering thruster may use the voltage and frequency as supplied, may use a transformer to reduce voltage or possibly use a power converter to change the power supply to match the requirements of the motor. The capacity of the main propulsion bus must be suitably sized to support the load and operation of the maneuvering thruster.

A typical design would have a transformer supplied by the main propulsion bus. The transformer would be used to step down the high voltages of the propulsion bus to supply a converter unit. As discussed in the main propulsion frequency converter section there are three principle converter types: synchroconverter, Current Source Inverter (CSI); cycloconverter and PWM Voltage Source Inverters (VSI). The PWM (VSI) would be the best suited to the requirements of a maneuvering thruster and would provide efficient power transfer with low harmonics on both the supply and motor sides. The unit would have nominal voltage rating between 450V and 2,000V and a power rating between 1MW and 2MW depending on the maneuvering thrusters design requirement. The PWM converter would be able to supply an induction motor and implement soft start and soft switching to prevent voltage 'sag' on the main propulsion bus. The induction motor would provide reliable, robust operation for the maneuvering thruster. With PWM the direction and amount of thrust would be controlled by changing the frequency and phase of the supply to the induction motor or by the use of the motor at a constant speed and employing a controllable pitch propeller. The constant speed motor using a controllable pitch propeller is seen as the most favorable application. Today's electric drive units containing a PWM converter and induction motor are available as one module. Alternatively, the system may be designed with two PWM converters powering an induction motor with two sets of windings. This increases reliability and in times when only partial power is available, due to damage or equipment failure, the maneuvering thruster can be operated with only one winding set in operation.

3. Design and Operation of Electro-Magnetic Aircraft Launching Systems

This section will present the first of the two systems currently under development that can be supplied from IES: the Electromagnetic Aircraft Launching System (EMALS) and aircraft recovery systems. EMALS was first investigated in the late 1940's with the advent of the first catapult launched aircraft [14]. However, electro-magnetic and power electronic device technology was not available to achieve the desired results compared with the steam catapult which is still used today.

The EMALS is again being considered because of advancements in the fields of electro-magnetics and power electronics [20]. The present EMALS design centers around a linear synchronous motor being supplied by a pulsed disk alternator through a cycloconverter [20]. Average power, obtained from a source on the ship, is stored kinetically in the rotors of the disk alternators. It is then released in a two to three second pulse during launch. This high-frequency power is fed to the cycloconverter which acts as a rising-voltage, rising-frequency source to the launch motor. The linear synchronous motor takes the power from the cycloconverter and accelerates the aircraft down the launch stroke, all the while providing real-time closed-loop control [20]. The average power required by EMALS is projected to be about 5.75 MW. Extracting this power level from the main propulsion bus is achievable in a ship utilizing the IES [20]. Figure 6-2 represents an envisioned EMALS launch motor located on the flight deck.

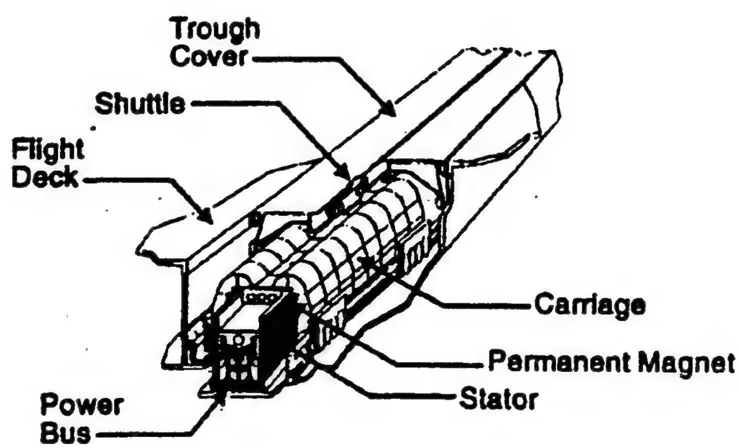

Fig 6-2. EMALS Launch Motor located on the flight deck [20].

The advantages offered by electromagnetic systems over steam systems are numerous. These advantages include improved performance capacity, reduced weight and volume, both derived from increased power densities. The system would also require less maintenance than current steam systems which require substantial supporting equipment. The use of EMALS further supports the use of electric propulsion and the IES on ships. The disadvantages to EMALS include quantifying and reducing the influence of the electromagnetic interference from the system to the ship and aircraft and accommodating the current reliability of the linear synchronous motor [20].

4. Design and Operation of Pulsed Energy Weapons

This section will present the second of the two auxiliary systems to utilize IES: the Pulsed Energy Weapon (PEW). The threat of anti-ship cruise missiles and the resultant shipboard countermeasures that must be employed to defeat them will demand new solutions, including high-energy weapons. The inevitability of high-energy ship systems for anti-ship missile defense or a variety of other emerging pulsed-power applications requires the Navy to explore how to affordably integrate these systems into future surface combatants [21]. The current development is tending toward the use of a capacitor-based Pulse Forming Network (PFN) supplying an Electro-Thermal Chemical (ETC) gun. Current designs employ an initial AC source supplying of 5kV from 120Hz to 800Hz [21]. The AC is converted to 15kV DC by a transformer and rectifier. The DC is then used to power the PFN. A typical PEW system could consist of a pulse weapon generator, diverter switch, rectifier/inverter, transmission cables, transformer, rectifier and weapon. Regardless of the design of the PEW, the system will require large amounts of power. Estimated power levels for proposed systems include are 4 MW, 10 MW and 20 MW [21]. Present Navy ships have no significant pulsed-power loads or large electric power sources to support the proposed power levels of a pulsed weapon [21]. The most likely source of power is the ship's main propulsion prime movers.

Current development has the power for the PEW being produced by a generator powered by a main propulsion gas turbine. There are four general configuration being considered. First, a direct drive propulsion plant will have a power take-off from the current double input gear set to a dedicated PEW

power generator. The design is such that one of the two main propulsion gas turbines could be dedicated to the PEW generator. The next two configurations both have a main propulsion gas turbine directly coupled to one generator. A diverter switch allows the generator to output to either the propulsion system or to the pulsed-power weapon system. The same generator in this case would be used for the main propulsion system and the PEW system, but at different times. One layout would take the electrical supply from the generator through a step up transformer to the rectifier. The other layout would condition the output from the generator prior to the transformer and rectifier. The output from the generator, for the conditioning layout, would go to a converter that would increase the electrical frequency. The fourth design is an electric propulsion system that has a single main propulsion gas turbine inputting to a gear set with twin outputs. One output would be to a main propulsion generator and the other to a dedicated PEW generator. The gear set design would allow for either the main propulsion generator or the pulsed weapon power generator to be operated at one time. The four types of configuration to power the PEW are presented in Figure 6-3.

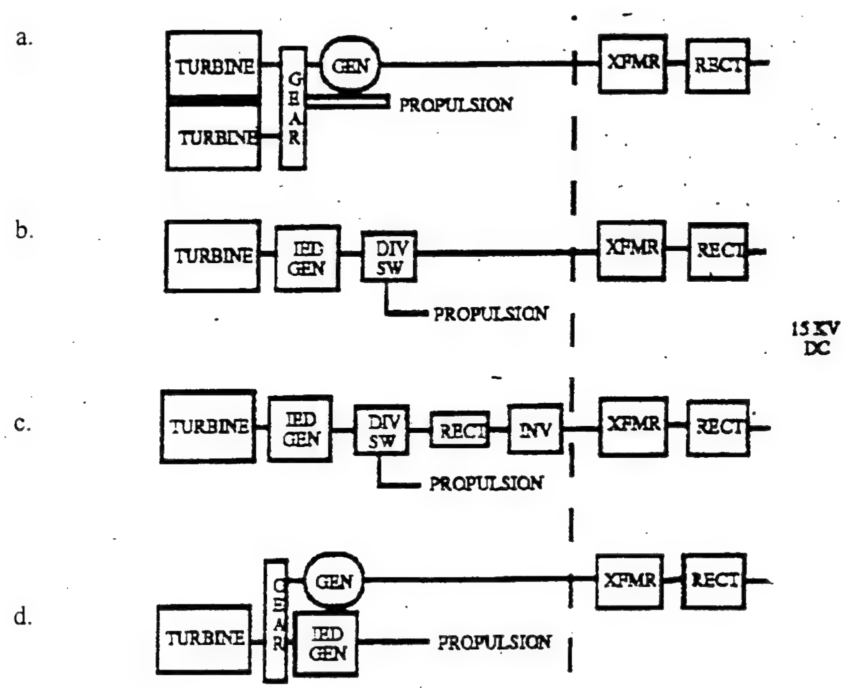

Figure 6-3 (a) Direct Drive Configuration, (b) Direct Couple Electric Propulsion without power conditioning, (c) Direct Couple Electric Propulsion with power conditioning (d) Geared Electric Propulsion with independent generators[21].

Of the four configurations for powering the PEW, only three are compatible with electric propulsion and IES. When comparing the various configurations there are several issues that must be addressed. The main issues are weight, volume, reliability and system performance. The configurations that use a reduction gear are the best options with regards to volume and weight of the PEW components. The size and weight reduction are achieved by having the pulsed weapon generators producing higher voltages at high frequencies and the elimination of the diverter switch. Electrical frequency is controlled by a step-up gear system that produces a higher speed output and the control of the gas turbine speed output driving the gear set. However, there are drawbacks to the use of gear sets in terms of hull noise and the complexity of the gear design for independent duel output. In the case of the electric drive using a double-output gear set, there would have to be a gear set and PEW generator for each gas turbine to achieve maximum redundancy.

The two middle configurations use one generator for both propulsion and the PEW systems. These configurations are the most suitable because they eliminate the need for gears, provide maximum redundancy for power to the PEW and integrate well with other ship systems. However, the disadvantage with using a common generator for both the main propulsion and pulsed weapon is that the optimum power requirements for the two systems are different. The first of the two configurations, generator output going directly to a transformer, is the least attractive from the standpoint of weight and volume [21]. The lower electrical frequencies of the generators for propulsion would force the step-up transformer to be large in size. The configuration where the power is conditioned by a converter unit to increase electrical frequency prior to the transformer has a reduced total system weight and volume compared to the unconditioned common generator design.

From the above information the two favored configurations would be the prime mover using a duel outset gear set and two generators, or the prime mover directly coupled to a single generator with power conditioning. Because converter units can be made very reliable and fault tolerant, the design using one converter for two generators provides a reliable system without the added volume or weight of having a conditioning converter with each generator. For all prime movers to be available for use with the PEW in the configuration with a dual output gear set, all prime movers would need gear sets and PEW generators.

From the comparison of the different configurations, the system that is best suited for use with an IES is the common generator with a line conditioning converter. This system has the best trade-off between weight and volume while still supporting electric drive. It is also the most reliable.

D. HARMONICS IN THE ELECTRIC PROPULSION SYSTEM AND IES

1. Frequency Converters Harmonics

There are three types of converters suitable for electric propulsion: synchroconverters cycloconverters and PWM voltage source converters. Currently, only the synchroconverter and the cycloconverter can operate at the power levels required for electric propulsion. Often times the operation of frequency converters results in significant harmonics in the phase currents which, in turn, cause large torque pulsations and vibrations for the propulsion motor [23]. The synchroconverter and cycloconverter can both be used in a 6-pulse or 12-pulse configuration. The 12-pulse configuration reduces the harmonic currents for both topologies and, in the case of cycloconverters, about 70% reduction in harmonics is achieved [6]. The cycloconverter has a significant improvement in the output wave harmonic distortion over the load commutated synchroconverter and can be improved further by utilizing a 12-pulse configuration. From the aspect of harmonics, the cycloconverter using a twelve-pulse configuration is the most desirable for a naval surface vessel [6]. However, synchroconverters are attractive in that they require a fewer number of power electronic devices and output frequencies higher than the supply frequency can be produced. Numerous studies of harmonic reduction has been conducted on the cycloconverter [6,23,24].

2. Effects and Reduction of Harmonics for Electric Propulsion Motors

Experience with electric propulsion systems has proven that the electric motors currently in use are not directly applicable to military applications [6]. This is particularly true when considering the effects of current harmonics on motor operation, and hence, the radiated noise from the ship due to the resultant torque fluctuations and vibrations [24]. Designs for warship electric propulsion systems have placed considerable effort in reducing harmonics from converter units and the ability of components and

the IES to operate with harmonics. Harmonic content from converters will have significant effects on the performance of the propulsion motor. Additional losses will occur, particularly in the stator and rotor windings and in the core. The magnitude of these losses depend on the specific operation of the converter and motor, although 18% losses is considered to be a reasonable estimate [6,23]. From the design of a warship electric propulsion system, the increased losses can be overcome by utilizing an overrated machine. To decrease the motor losses, harmonics should be minimized. However, the effects of current harmonics giving rise to shaft torque pulsations and radial core vibrations are of a far greater concern than efficiency. These torque pulsations and core vibrations are particularly undesirable in a warship because of associated noise radiated from the propeller and the hull.

To reduce the effects of harmonics, the propulsion motor parameter design can be optimized to minimize mechanical resonances and vibrations. The optimization of the motor design could use the following parameters: motor impedance, slotting, chording and motor stiffness [23]. Increased impedance is accomplished by adding turns to each phase of the stator. The increased impedance acts like a filter for reducing harmonics. Increasing the impedance of the propulsion motor has the advantage of reducing the stator core vibration, but results in a loss of performance. Slotting effects the number of stator slots per phase per pole. An increase in the number of slots increases the impedance of the motor. Slotting can also be used to reduce the resonant frequencies in a desired speed range of the propulsion motor. Chording refers to the pitching of the stator windings. Chording is used to optimize the magnetic flux harmonics. An increase in rotor stiffness is used to reduce the vibration caused by natural resonant frequencies. An increase in rotor stiffness is accomplished by increasing the core depth. This has little effect on the electro-magnetic circuit and can easily be achieved. The penalties are a bigger, heavier and more expensive machine.

E. SUMMARY OF TOPICS COVERED

An overview of the current and developing technology for marine electric propulsion systems and an IES has been presented. Included in this overview are design consideration and the architecture of various subsystems that are in operation or being considered for use with electric propulsion and an IES.

The advantages and disadvantages of components and architectures have been investigated. With the data available, a good foundation has been made available to facilitate operation, controls and design for an electric propulsion system incorporating the IES. In the following three chapters the operation and controls of the various subsystems, control topologies for the frequency converters and mathematical analysis of a six-phase synchronous motor are set forth to aid in the future computer simulation of an electric propulsion system incorporating the IES.

VII. CONTROL AND OPERATION OF THE INTEGRATED ELECTRICAL SYSTEM

The previous chapters identified the components and general operation of the components of the electric propulsion system and the IES. The first part of this chapter will review how the ship will operate its propulsion system depending on the various components that comprise the system. The second part of this chapter will introduce how the IES will control the Ship's Service Electrical System (SESS). The final section will review controls of auxiliary loads being fed from the IES.

A. SHIP'S PROPULSION CONTROL AND OPERATION

1. Types of Propulsors

This section contains a description of the operation and the control of the electric propulsion system. The propulsion system for a ship is the means by which the ship is propelled through the water and provides the necessary control for speed and direction of motion. There are various methods for propelling ships through the water, ranging from sail and hand oars to power machinery driving devices that impart energy to water. With the advent of steam power for ships, the side or stern paddle wheels were used to impart energy to the water. In the late 1800's the screw propeller was developed to impart energy to the water [25]. The screw propeller is fully submerged allowing the maximum amount of energy to be transferred to the water (highest efficiency) and the connection between the prime mover and propeller was a simple shaft [25]. The screw propeller is still commonly used with propulsion systems for displacement hulls. There are other methods of imparting energy to the water for a propulsion system including water jets, vertical axis propeller, pump jet and contra-rotating propellers. The most appropriate for a surface combatant remains the screw type propeller [25].

Regardless of direct drive or an electric propulsion system, a screw propeller is the most common method of imparting motion to the water. As a screw propeller rotates or moves downward, it pushes water down and back. At the same time, water must be replaced behind the blade to fill the space left by the downward moving blade. This results in a pressure differential between the two sides of the blade, a positive pressure or pushing effect on the underside or backside and a negative pressure, or pulling effect,

on the top side or front side of the blade. This action occurs on all the blades around the full circle of rotation of the propeller, so the propeller is both pushing and being pulled through the water. The screw propeller draws water in from its front end at a larger diameter than the propeller diameter. As the propeller spins, water accelerates through it, creating a jet stream of higher velocity water behind the propeller [25]. This exiting water jet is smaller in diameter than the actual diameter of the propeller and this water jet action of pulling water in and pushing it out adds momentum or acceleration to the water which results in a force which is called propeller thrust. The thrust is imparted to the ship's hull through thrust plates and thrust bearings [25]. There are two types of screw propellers used today: fixed pitch and controllable pitch. Both are suitable for electric propulsion. The method of control and operation for an electric propulsion system utilizing a Fixed Pitch Screw Propeller (FPSP) and Controllable Pitch Screw Propeller (CPSP) are discussed along with corresponding advantages and disadvantages. This section concludes with a comparison and analysis of which propeller type is suitable for the electric propulsion system.

2. Operation of a Fixed Pitch Screw Type Propeller

The FPSP is the most common form of propulsor for surface ships. Speed control is accomplished by changing the speed of the propeller [25]. As the propeller's speed is increased, the amount of propeller thrust increases, moving the ship at a faster speed. The speed of the ship is proportional to the speed of the propeller. For a direct drive ship the propeller is driven by reduction gears or directly coupled to the prime mover. The prime mover can be any of the types introduced in Chapter IV. Varying the output of the prime mover effects the speed of the propeller and changes the ship's speed. The faster the prime mover's speed, the faster the speed of the ship.

The common issue of altering the direction of rotation of the FPSP is addressed now. There are different methods to change the direction of the propeller rotation based on the type of prime mover and the connection of the propeller. A reversing pinion could be used when a reduction gear is employed with the propulsion system. With steam turbines, even though they use reduction gears, a separate astern turbine that rotates the opposite direction is employed. With direct coupled drives, for example slow-speed diesel engines, the rotation of the prime mover is reversed. When going from the ahead direction to

operating astern, the propeller needs to be stopped, the method of reversing enabled and rotation restarted. In some cases the shaft is allowed to stop naturally. To stop the shaft faster mechanical brakes are used. These brakes are engaged after power have been removed. The mechanical brake is also used to stop the shaft and propeller in emergencies.

A propulsion motor has the same rotational speed as the propeller if directly connected. If a reduction gear is installed between the motor and the propeller, a fixed-speed reduction will occur between the two. With an FPSP the propeller is optimized for efficiency and placed in the best location on the ship to provide thrust in the forward direction [25]. For the FPSP, cavitation is also minimized for ahead propulsion of the ship.

As previously stated, propulsion motor speed is controlled by the frequency of the power supply. The frequency range of the converter would allow for the propulsion motor to operate from a speed of zero to maximum rated speed. In general an ordered speed signal is sent to the controls for the converter [6]. The converter controller then translates the speed order to an output frequency. The controller will then adjust the converter output frequency and any other machine inputs as appropriate until the ordered speed is established. This frequency to speed relationship is maintained through the feedback controls of the propulsion motor to the converter regardless of load changes. The control of speed is accomplished the same way regardless of the rotation of the propeller. Controls for the synchroconverter are discussed in detail in Chapter IX.

There are two different starting points for which the control of rotation is enabled. The first is from a condition where the propulsion motor and propeller are stopped. The second condition is when the propulsion motor and propeller are in operation. In the first condition, the control of the propulsion frequency converter is all that is required for ahead or astern direction. With a frequency converter, the firing sequence of the power electronic devices are controlling the output phase sequence applied to the propulsion motor [6]. When ahead orders are sent to the converter controller the electronic devices fire to provide a phase sequence for motor operation in the ahead direction. When astern orders are sent to the converter, a different phase sequence is produced for the propulsion motor to operate with opposite rotation.

The second condition for the control of the direction of motion is when ahead or astern motion is already in progress. When a FPSP is used, it must be stopped before changing the direction of the rotation. There are several issues that must be addressed. First, the frequency converter must go from providing power to the propulsion motor at the given speed and direction to providing no power to the motor. At this point the converter will have all of its power electronic devices disabled [26]. Once power is removed, the propeller, shaft and propulsion motor must be stopped by a braking system to allow the motor to be started in the opposite direction. Once the shaft has stopped, the converter again sends power to the motor in a different phase sequence causing the propulsion motor to rotate in the opposite direction. Once rotation is occurring in the new direction, propeller speed is controlled by the converter's output frequency.

There are disadvantages to using an FPSP with electric drive systems. In particular the propulsion motor always experiences the load of the propeller turning in the water. An FPSP will develop thrust as soon as it begins to rotate. For added measures of safety and redundancy two sets of windings, as was addressed in the propulsion motor section, are used for the propulsion motor with each rated at 50% of total output power [26]. When starting the motor with only one set of windings, the load from the FPSP will cause higher currents in the single set of windings and slower responses to ordered speeds. The slower responses are caused by the same loading for a single set of windings where there are normally two sets of windings [26]. The slower responses to ordered speeds may pose a danger when the ship is operating in confined waters. Also, the FPSP is optimally designed for ahead operation. An electric propulsion motor produces the same amount of power in both directions of rotation. So an FPSP does not take advantage of the available power from the electric propulsion motor when operating astern. Also, when the ship is changing direction, the power is removed from the propulsion motor. This causes problems with the voltage levels on the main bus and the loading on the prime movers. If voltages vary considerably, damage may occur to other systems. For the prime mover, the removal of a major part of its load may cause over-speed and fluctuations in the output frequency and voltage [26].

3. Operation of a Controllable Pitch Screw Type Propeller

The CPSP is considerably different than the FPSP. The CPSP is fitted with blades that can be rotated around axes normal to the drive shaft. Rotation of the blades are accomplished by directing hydraulic fluid down the shaft which operates pistons that position the propeller blades. In the hub (the area at the end of the shaft that holds the blades) the hydraulic fluid is directed to the pistons by a shuttle value. The shuttle valve is operated by a control rod that also runs the length of the shaft. When a pitch order is given the control rod positions the shuttle valve to allow the hydraulic fluid to move the pistons, in turn changing the pitch of the propeller blades. When the blades are in a correct position a feedback from the hub causes the control rod to reposition the shuttle valve maintaining the hydraulic fluid in the pistons. The fluid holds the piston and the blades in position until a new pitch order is given [7]. The pitch can be altered to satisfy a range of operating conditions of the propulsion system. The ability to control the pitch of the propeller is where the term controllable pitch originates [25]. Pitch control is used to match the torque being developed by the propulsion motor to the load torque of the propeller at a given speed.

A propulsion system utilizing a CPSP uses both pitch and propeller speed to provide for the control of ship's speed. Total control of thrust from 0% to 100% is accomplished through a combination of pitch control and speed control of the propeller. The general operation of a propulsion system using a CPSP is as follows. At zero thrust and zero speed the propulsion motor and propeller are turning at a predetermined speed with zero pitch on the propeller. The predetermined speed for an electric propulsion system is based on the operation of the frequency converter, propulsion motor and propeller. For example with a synchroconverter, a logical predetermined speed would be where the propulsion motor could support natural commutation. When an order is received by the system, the propeller pitch will increase, producing thrust while the speed of the propulsion motor and propeller remain at the predetermined value. As the orders for increased speed are received, the pitch will continue to increase, delivering more thrust. Pitch control operating at a fixed speed allows for speeds up to 14 knots depending on the ship design [25]. Upon reaching the top speed achievable with the use pitch control alone, a combination of pitch control and speed control of the propulsion motor are used. Once the propeller has reached its maximum pitch, speed control of the propulsion motor is used to achieve the maximum speed for the ship. With an electric

propulsion system the use of converter frequency control determines the speed of the propulsion motor in the same way for both FPSP and CPSP.

The CPSP can vary the pitch of thrust control for a range of speeds in one direction and can completely reverse the pitch producing astern thrust. Control for a range of speed in the astern direction is also controlled by varying the pitch and speed as required. The big difference when using a CPSP is that the rotation of the shaft remains the same for ahead and astern operation. The need to stop the propulsion motor, shaft and propeller is eliminated.

The advantages to the CPSP are numerous. First, the pitch can be changed to avoid overloading of the propulsion motor or causing high currents at startup or large speed changes [26]. Also, during operations when only one propulsion motor winding is available, the pitch can be controlled to increase the response of the propulsion system for maneuvering [26]. Second, variation in thrust and in turn speed control for maneuvering can be made more rapidly. Further, changes in pitch can occur more rapidly than changes in the speed of the propeller [25]. The following table shows comparative calculations for effects of a fixed-pitch mechanical drive, fixed-pitch electric drive and a controllable-pitch electric drive in terms of stopping distance from full power for a twin screw ferry of 590 feet in length.

TYPE OF PROPULSION	DISTANCE TO STOP
FPSP WITH DIESEL MECHANICAL DRIVE	2000 FT
FPSP WITH DIESEL ELECTRIC DRIVE	1610 FT
CPSP WITH DIESEL ELECTRIC DRIVE	1260 FT

Table 7-1. Comparison of stopping distances using different types of propellers and drives [25].

Even though there are strong advantages to be gained by using a CPSP, there are disadvantages that need to be considered. The CPSP is a mechanically complex device that is limited in the total power that it can transmit due to forces on the rotating blades [25]. The system also increases the equipment that is located with the propulsion motor and in turn may increase the size of the motor. If the current method

of implementation for CPSP is used, the motor rotor would be designed to have paths for the hydraulic fluid, control shaft and follow-up shaft. The space for these paths increases the diameter of the rotor while having an effect of weakening the rotor. The CPSP also has a larger diameter hub than the FPSP which effects cavitation performance and in turn efficiency and noise produced in the water.

A point that should be made about the CPSP is that in a case where pitch control is lost or limited, the ship still has the ability to change direction and speed. If there is any pitch on the propeller, the ship can be maneuvered in the same way as a ship fitted with a FPSP. The system may not be able to deliver full power or be as responsive, but the ability is still available. Based on the information provided the use of CPSP is the best choice for electric propulsion systems.

4. Braking System for Electric Propulsion

Regardless of the propulsion system using fixed-pitch or controllable-pitch propellers, a braking system for stopping the shaft is required. In the case of a FPSP the brake is required to stop the shaft to change direction of rotation and in emergencies. With the CPSP the brake is only used when the shaft is required to be stopped in emergencies. During emergencies the motor, shaft and propeller may need to be stopped and held stationary for long periods of time. The brakes must have the ability to hold the propulsion motor, shaft and propeller stationary even while the ship is underway using alternative sources of propulsion. These emergencies would include bearing failure, failure of the stern tube seal, when the propeller is in danger of being fouled or damaged and damage to the propulsion motor. There are two choices for braking the propulsion motor, shaft or propeller. The first method is to use a mechanical brake. Mechanical brakes are currently used on direct drives propulsion systems. With electric propulsion the design of the propulsion system is not limited to using a mechanical brake to stop rotation. Which leads to the second method of braking, the dynamic brake. Dynamic braking is designed to use the synchronous motor as a generator where the power produced is dissipated by a bank of resistors. The drawback to using a dynamic brake is the need to continue to have power to the rotor in the case of the wound-rotor synchronous motor and the need to have controls from the motor to adjust for changing torque on the shaft. If the propulsion motor windings or the field excitation system are damaged, the dynamic braking system

can not be used. Dynamic braking requires the use of the all windings and a supply for field excitation. In the event that the motor, shaft and propeller need to remain stationary while the ship is underway, the dynamic braking system still requires the motor to operate. For these reasons a mechanical brake is a better choice.

B. SHIP'S SERVICE ELECTRICAL SYSTEM OPERATION AND CONTROL

The ship's service electrical system has two sections for operation and control: the electrical distribution system and the ship's service generator. There are two issues to be addressed with regards to the SSES control: the controls for supplying the SSES from the main propulsion bus and the control of the Ship's Service Electrical Generators (SSEG) for operation. The SSEG can operate supplying power to the main propulsion bus or to the ship's service load only.

The IES's primary operation is to provide power from the main propulsion bus to the users. One of the users is the SSES. Two architectures have been examined for the SSES, the AC system and the DC Zonal Electric Distribution System (DC ZEDS). The operation for the AC system has only fixed elements. The main bus voltage is supplied to step-down transformers of the SSES. After the transformers reduce the voltage to a level for the SSES, it is distributed throughout the ship. Controls for the AC zonal system are the same as currently used today. Breakers, controllers and special power conditioning components are installed for the various components of the SSES. There are two additions to the AC system that must be considered. The first addition is ground detection devices at the output of the transformers. A ground may develop on the output side and will not be reflected to the main bus. So ground detection needs to occur after the transformer. The second addition is overload and fault protection for the transformers that are being supplied from the main propulsion bus.

The DC ZEDS involves more complicated controls. The rectifiers being fed from the main bus must monitor both input and output parameters. The rectifier must adjust for changes in the main bus that are caused by other loads, including propulsion, maneuvering thrusters and auxiliary electrical systems. The rectifiers must also be able to adjust to the changes on the DC buses caused by intra-zonal disturbances.

The ship's service generators must have the ability to operate in three different conditions. The first condition is when the SSEG is providing power to the main bus in conjunction with one of the main propulsion generators. In certain operating configurations, power required for propulsion and the IES may exceed a single propulsion generator rating but not be large enough to require the use of a second main propulsion generator. For these conditions the SSEG will operate to supply power to the main propulsion bus. The SSEG must match the frequency and voltage of the main propulsion bus within a set percentage before the generator can be paralleled to the main propulsion bus and provide power. The control of frequency is accomplished by the governor controls on the SSEG prime mover. If the frequency of the generator is lower than the main bus frequency the governor control is increased, in turn increasing the output frequency. If the SSEG is more than 10% higher than the frequency of the main bus, then the governor control is decreased, in turn reducing the output frequency. The voltage control is accomplished by the field excitation of the generator. The voltage must be within 10% of the main bus voltage. After the SSEG is supplying power to the main bus, automatic governor and field excitation controls maintain the frequency and voltage level at a preset level.

The next condition involves the operation of the SSEG providing power to the main bus for supplying the ship's service load only. As previously stated, the SSEG is used to provide for low ship's service load conditions such as at anchor. In this condition the SSEG may provide power to only the main bus that is connected to either the AC transformers or the DC ZEDS rectifiers depending on the type of ship's service distribution. In this condition the controls are standard for most generators. As the load changes, the SSEG governor and field excitation control will adjust to maintain the set level of frequency and voltage [27].

The last condition occurs when the SSEGs are providing power to the main propulsion bus for propulsion power and ship's service electrical power. In this condition the SSEG's are the only power sources for both propulsion and the SSES. The propulsion can be provided by the main propulsion motor powering the propeller or by the maneuvering thrusters. In the case of having the main propulsion motors powered by the SSEGs, there must be a limit on the power the main propulsion motors draw from the generators. It is possible to overload the ship's service generators when using the main propulsion motors.

The use of the maneuvering thrusters consumes considerably less power than the propulsion motors. A typical maneuvering thruster will be designed so that the ship's service load and 50% of the thruster's power requirements can be supplied from half of the installed SSEGs available for a margin of reliability and safety. The controls for the SSEG must have the ability to operate with the harmonics that are produced by the main propulsion motor's frequency converters [27]. When operating the maneuvering thrusters, the controls are the same as when supplying the ship's service load alone.

C. AUXILIARY ELECTRICAL SYSTEMS OPERATION AND CONTROL

This section includes a discussion of the different auxiliary electrical systems previously listed and how they operate with relation to the IES. The auxiliary electrical systems may all operate differently and have individual methods for control. The auxiliary electrical systems that will be discussed are cargo handling equipment, maneuvering thrusters, Electro-Magnetic Aircraft Launching System (EMALS) and Pulse-Energy Weapons (PEW). The detailed controls for each of the auxiliary electrical systems is not addressed.

There are two options when supplying power to the cargo handling equipment from the IES. The first option is for the equipment to be supplied off of the SSES. The IES components (transformers for AC system and rectifiers for DC ZEDS) connecting the SSES to the main propulsion bus must have the capacity to operate normal loads and support the additional load when operating cargo handling equipment. This may result in higher ratings or multiple connecting components for the main propulsion bus and the SSES than would be required during normal operation. The higher ratings for components or increased numbers will increase cost and space requirements. The second option is to supply the power from the main bus directly to cargo handling equipment. The power from the main bus can either be used at the main propulsion bus voltage and frequency level or must be converted to meet the requirements of the cargo handling equipment. In most cases the design would attempt to avoid the need for converting power to avoid increases in cost and space for more equipment.

Regardless of the method that power is supplied, the operation of cargo handling equipment may require an increase in power that exceeds the rating of the available SSEG. In this situation a main

propulsion generator can supply sufficient power to the main bus for the SSES and cargo handling equipment. This is one of the advantages of electric propulsion using the IES.

The controls for the cargo handling equipment would be similar to other large electrical loads aboard the ship. When the SSES is used to supply the cargo handling equipment, the controls for the rectifiers and the controls for the generators supplying the main propulsion bus feeding the SSES must be able to maintain their set voltage and frequency levels. The main propulsion bus or SSEG must have the power capacity to operate all equipment that is being supplied at one time. The components of the IES must be able to compensate for load changes caused by the cargo handling equipment operation.

The operation of the maneuvering thrusters can be compared to the operation of the main propulsion motors. The maneuvering thrusters can have fixed-pitch or controllable-pitch propellers. The maneuvering thrusters are supplied power directly from the main bus. A Pulse-Width-Modulated Voltage Source Inverter (PWM VSI) can be used due to the lower power (1MW to 2 MW) requirements of the maneuvering thrusters compared to the high power (15MW to 25 MW) units used for main propulsion. The PWM VSI has the advantage of being able to work with both synchronous or induction motors. The PWM VSI converts the input power from the main bus to voltages and frequencies to be used by the maneuvering thruster motor. Speed and pitch control can be used to vary the amount of thrust that is delivered. With some types of maneuvering thrusters, only pitch control is used to adjust the direction and amount of thrust. Normally no braking system is installed for a maneuvering thruster. The IES must be able to maintain its voltage and frequency levels while the maneuvering thrusters are in operation regardless of the configuration of the generators providing the power.

The next two auxiliary electrical systems are both unique in the way they operate and are controlled. The EMALS can take power directly from the main bus and condition the voltage and frequency as required. The EMALS would impose times of peak loading while the system is being readied to launch aircraft. Once the system is ready to launch an aircraft, the load on the main bus is very small. EMALS is provided with its own internal energy storage device. After launching the EMALS would again show a period of high power demand. The EMALS has intermittent use with short periods of high demand. The ship's generators must be able to supply the high demands while still supplying power to the

remainder of the ship. An option that is available is to have one of the main propulsion generators supply power directly to the EMALS when operating. The design of the electrical propulsion system would have to take into account the use of a main propulsion generator being dedicated to the EMALS. EMALS would be used on aircraft carriers where the extra space is available to have greater numbers of main propulsion generators.

The PEW draws all of its power directly from a main propulsion generator unlike the EMALS that can draw power from the main bus. Current designs call for a main propulsion generator to have its total power output dedicated to the PEW when in operation. This means reducing the power available to the main bus for ship's propulsion, ship's service electrical and auxiliary loads when operating the PEW. In an IES the system control must be able to operate with changes in the amount of power available [27]. The maximum speed would be reduced to account for the lose of power from the propulsion generator being diverted from the main propulsion bus to the PEW. After the diverter switch converters would condition the voltage and frequency to meet the requirements of the PEW.

Both the EMALS and the PEW are under development. The use of common supplies of power for the operation propulsion, ship's service, maneuvering thrusters and auxiliary systems is one of the primary advantages to electric propulsion using the IES.

D. ELECTRIC PROPULSION AND IES OPERATION AND CONTROL

The IES's overall operation and control has several issues that must be addressed. The first issue is that the system must be able to supply the power required to operate the total load placed upon it. The second issue is that with the various types of loads, the system must be able to maintain set voltage and frequency levels. The third issue is the ability of the system to detect faults and operate with or isolate faults without the entire system becoming crippled. All of these issues are taken into account on individual systems that are in operation today. For example, if one generator fails on a direct drive ship with three dedicated ship's service generators and two operating at any one time, the automatic load shedding quickly reduces the load until the remaining generator is brought on-line. The loss of a ship's service generator has no effect on the operation of the propulsion system of the ship; the loss of a ship's service generator only

effects the SSES. With the IES the issues of operation and control must recognize that a single failure can effect all of the subsystems attached to it. For example with a ship's speed of 22 knots and a ship's service load of 1,800kW, an IES might have one main propulsion generator and one ship's service generator supplying the main bus. If the main propulsion generator fails, the load will far exceed the rating of the SSEG. If no action is taken, the SSEG would be over loaded and disconnect from the main bus leaving the ship without ship's service electrical power and propulsion power. The failure of one component in an IES effects all subsystems.

For the remainder of this section a ship with two main propulsion prime movers, two ship's service generators, two 12-pulse synchroconverter units and two double-wound synchronous motors each driving controllable-pitch-propeller will be used for examples. The ship is configured so that a main bus supplies power to the propulsion system, DC ZEDS, maneuvering thrusters and PEW. This is the basic design for a future surface combatant that would compare to the FFG-7 class of today. This does not limit the use of the IES on other types and sizes of ships, but this is a representative case.

The first item to ensure with an IES is that power is available under various operating conditions. A typical operational configuration is a ship underway. The load on the IES would determine the generator configuration. An example may be a ship going five knots with a normal electrical load. Two ships service generators would be online supplying either the propulsion motors or the maneuvering thrusters and the ship's service load. An example of an opposite extreme would be all ship's service generators and main propulsion generators on line with one main propulsion generator supplying a PEW and the remainder of the generators supplying the electric propulsion system at the maximum speed and the SSES at a maximum load. The IES must maintain at least one ship's service generator online to supply the ship's service electrical system. Without this minimum, the ship could not function or restore operation after a causality.

In any configuration, controls for the IES encompass three items. First, the governor controls for the prime movers and field excitation control for the generators must maintain power levels required for the load and the voltage and frequency levels supplied to the main bus [28]. Controls are constantly adjusting as the load changes on the main bus due to changes in the ship's service electrical load and

changes in speed. The second item is that the IES control and sensing units must be able to operate with harmonics and transients on the main bus that are caused by main propulsion converters and rectifiers operating simultaneously. The third item is the control for the IES must be able to detect faults in system, isolate faults and reconfigure the system to maintain the current loads and, if this is not possible, intelligently reduce the load to match the supply [27]. These faults can range from a ground on the main propulsion bus to a failure of a generator supplying the main bus. In cases of grounds, the sections of grounded main bus must be located and isolated. In cases of generator failure, the IES must be able to automatically reduce the load on the system and reconfigure other generators to re-establish the supply power for the current condition if possible. If the reconfiguration of the remaining generators is not possible, then the IES must be able to reduce its loading automatically so that power is not completely lost.

The operation and control of the IES are major undertakings due to the symbiosis of the numerous systems. The basic concern is to maintain power to the ship's service systems in the most demanding situation. The redundancy of the system is driven by the design requirements placed on the ship.

VIII. CONTROL SYSTEM FOR A DC LINK SYNCHROCONVERTER AND SYNCHRONOUS MOTOR IES

A. REQUIREMENTS AND MODES OF CONTROLS

1. Requirements for Electric Propulsion Control

The ability to control a ship's maneuvering by controlling the direction of rotation and speed of the propulsion motor and/or the pitch of the propeller was addressed in Chapter VII. The control of the converter unit to adjust motor operation is an integral part of the control of the propulsion system. The converter provides the ability to change the speed of the propulsion motor, the direction of rotation and also maintains a set level of speed for the propulsion motor during steady-state operation of the propeller. The control system for the converter and propulsion motor has four basic operational modes: starting, steady-state speed, transition speed (accelerating/decelerating) and electrical dynamic braking. The issue of electrical dynamic braking is not considered since the use of mechanical brakes, as discussed in Chapter VII, is the most effective solution for braking.

The first operation of the control system is to start and accelerate the propulsion motor. The converter must have the ability to operate at low frequency and voltage to start the synchronous motor. In the process of starting the converter, controls must prevent over-current conditions and major disturbances in the power supply. This includes over-current conditions that may arise during large changes in speed or torque due to disturbances at the propeller. The second operation of the control system is to react and implement a change in the speed command. The speed of a synchronous motor is controlled by the supply frequency. For reasons of maneuvering and safety of operation, these requested changes in propulsion motor speed must be accomplished quickly and accurately. The third operation of the control system is to maintain the ordered speed for the propulsion motor. The control system must be able to react to changes in the propulsion motor's loading very quickly. Changes in the load on the propulsion motor can occur from wave action on the ship's hull, the operation of the rudder being used to change the ship's heading and from environmental conditions such as high wind and seas that reflect changes on the propeller thrust.

2. Modes of Control Designs for Converter Operating with Synchronous Motors

With variable frequency control of a synchronous motor, there are two modes of operation that are possible: true synchronous mode and self-controlled mode. The true synchronous mode is used with voltage source inverters and employs an independent oscillator that programs the frequency of the inverter. This mode is often used for constant speed control and allows for a simple design for the controller. Due to problems with hunting and stability, this mode is predominately used in multiple synchronous-reluctance and permanent-magnet motor drives in applications such as paper mills, textile plants and fiber-spinning mills [29]. The second mode is the self-controlled mode in which the supply frequency to the motor is changed automatically so that the armature magnetic field is locked in unison with the rotor of a synchronous machine. The self-controlled mode can be used with nearly all types of variable-frequency converters which includes voltage source inverters, current-source inverters, current-controlled PWM inverters and cycloconverters. High-power and high-speed electric drives can be found using self control with load commutated current source converters or cycloconverters in steel mills, traction devices, conveyers and compressors [30]. Self control is commonly found in ship's propulsion systems such as the USCG *Healy* and the *QE II* [11] .

Self-controlled variable speed synchronous motor control has a number of advantages over synchronous control and induction motor or DC motor variable speed drives. Since the rotor is always locked in synchronism with the stator rotating field, stability and hunting problems are eliminated. Self-controlled synchronous machines can be used in high-speed and high-power applications where DC or induction motor systems are either inappropriate or incapable of operating. The power factor of a wound-rotor synchronous motor can be controlled by controlling its field current. The ability to control power factor minimizes the KVA rating, converter and machine cost, losses in the variable frequency supplies, and maximizes the motor power output [29]. Also, the self-control mode makes use of load commutation which reduces control components for the inverter. The cycloconverter can be controlled to produce either a voltage or current source using the self-control mode of operation [29].

B. ANALYSIS OF THE SELF-CONTROL MODE FOR ELECTRIC PROPULSION

1. Principles of Self-Control Mode

In this section, a DC link current source synchroconverter is used to demonstrate a control architecture for an electric propulsion system utilizing a self-controlled synchronous machine. The self-control mode requires an input related to the position of the rotor. Rotor position sensors are used to track the speed of the rotor. The control input is achieved through optical or magnetic sensors or from armature terminal voltage sensors. The rotor position indicators are used to generate reference signals for the firing of the electronic devices in the inverter where the most common device is the thyristor. As the rotor speed changes, the rate of firing the electronic devices in the inverter is altered so that the motor's supply frequency forces the stator field speed to match that of the rotor. Because the rotor and stator fields move together for all operating points the motor does not suffer from oscillations and instability due to load disturbances [30]. In addition, the electromagnetic torque can now be controlled electronically by adjusting the angle between the stator field and the rotor by delaying or advancing the switch gating signals [30].

After the rotor position indicator has provided the reference signal to fire the electronic device, the electronic device is then commutated (turned off) by the back Electro-Motive Force (EMF) voltage from the stator windings. This is termed load commutation and is possible due to the leading power factor that can be produced by the synchronous motor. Without a leading power factor, forced commutation is required to turn the electronic device off. The forced commutation is supplied by additional circuitry external to the electronic device. The use of forced commutation increases the complexity of the controls for the inverter and becomes very inefficient at high power levels for electric propulsion.

2. Operation of the Current Source Inverter with Synchronous Motor

Figure 8-1 shows a current source inverter feeding a synchronous motor. The DC link current, I_d, is established by a six-pulse rectifier fed from a three-phase AC source and is then routed to the inverter. The controlled rectifier and the inductor, L_d, constitute a current source. The large inductance value in the DC link reduces the amount of ripple in the DC current and prevents interference between the operation of

the rectifier and the inverter. The inductance per phase of the synchronous machine is referred to as the commutating inductance. The commutating inductance is taken to be the subtransient inductance of the synchronous motor due to the very short duration of commutation transients. The voltages V_{an}, V_{bn} and V_{cn} are the excitation voltages induced in the armature due to the flux linking the armature [30].

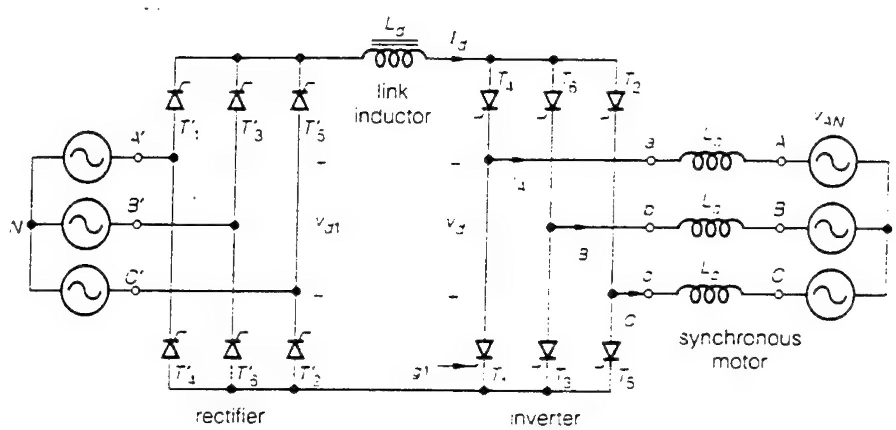

Figure 8-1. Schematic diagram of a current source inverter supplying a synchronous motor [30].

The operation of the current source inverter with load commutation is depicted in Figure 8-2. The electronic devices in the inverter are fired in the sequence in which they are labeled and each conducts for approximately 120° of a cycle [30]. When an odd-numbered electronic device is gated, the previously odd-numbered device is commutated. This also holds true for the even-numbered devices. In an ideal situation only two electronic devices will be conducting at the same time. Current can be transferred from a device that is being turned off to a device that is being gated when the corresponding line voltage is positive. When the line voltage is positive, it acts to forward bias the incoming device and reverse bias the out-going device. The commutating inductance of the synchronous machine prevents the instantaneous transfer of current as illustrated in Figure 8-2. As a result, three devices are conducting for a small interval of time at each switching instance. This commutation delay angle, u in Figure 8-2, is a function of the link current, rotor speed and machine parameters.

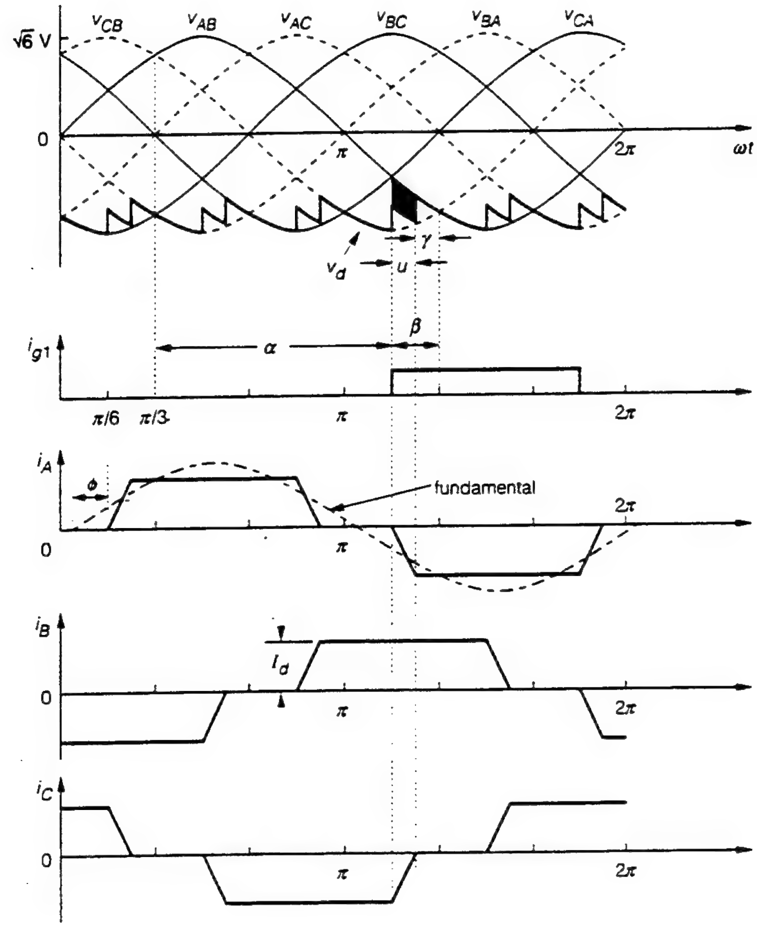

Figure 8-2. Motor phase voltage and current waveforms for a current source inverter feeding a synchronous motor using load commutation [30].

3. Analysis of Operation of a DC Link Synchroconverter and Synchronous Motor

Motor operation is enabled by applying a firing angle α greater than 90°. This angle is the angular delay from the points of natural commutation for the thyristors Figure 8-3 represents the equivalent circuit for the commutation interval where current is transferred from T_5 to T_1. The starting point of the analysis has T_5 and T_6 conducting and the DC-Link voltage given by $V_d = V_{CB}$. T_1 is fired at angle α, With constant DC Link current I_d during this interval, the positive line voltage V_{ac} reduces i_{T5} to zero while permitting i_{T1} to increase to I_d in the period u, the commutation-overlap angle. The point where V_{ac} is zero and positive going is termed the natural point of commutation. The turn-on of T_1 can be delayed up to approximately 160° from the natural point of commutation and still reliably commutate the electronic

device [22]. With T_5 now commutated, devices T_1 and T_6 are conducting and V_{AB} equals V_d. The waveforms of the DC Link voltage V_d and the motor's phase currents, i_A, i_B, and i_C, are shown in Figure 8-2. With a negative average value of V_d and positive I_d, real power flows from the DC Link to the synchronous motor.

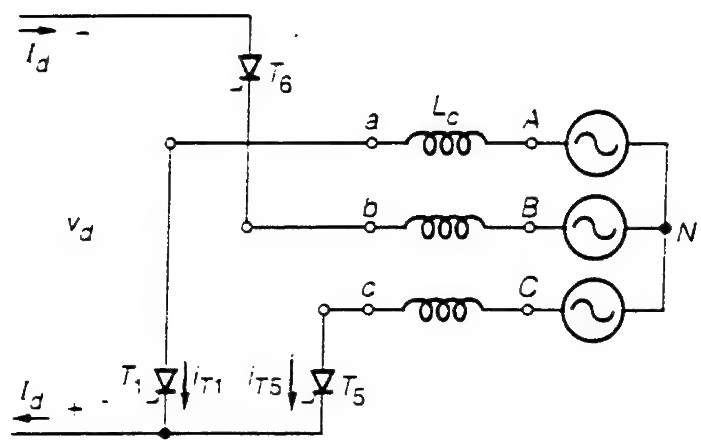

Figure 8-3. The equivalent circuit for analysis of a current source inverter supplying a synchronous motor using load commutation [30].

The following computational analysis is performed to uncover the relationship governing the commutation overlap angle u. First, at the beginning of the interval depicted in Figure 8-3

$$i_{T1} + I_{T5} = i_d \qquad \text{Eq 8-1}$$

$$L_c\,(\frac{di_{T1}}{dt}) - V_{AC} - L_c(\frac{di_{T5}}{dt}) = 0 \qquad \text{Eq 8-2}$$

Assuming constant I_d, Equation 8-1 implies

$$-\frac{di_{T1}}{dt} = \frac{di_{T5}}{dt} \qquad \text{Eq 8-3}$$

Substituting Equation 8-3 into 8-2 yields,

$$\frac{di_{T1}}{dt} = \frac{V_{AC}}{2L_C} \qquad \text{Eq 8-4}$$

Assuming that V is the RMS value of the phase voltage, it follows that V_{AB} is given by

$$V_{AB} = \sqrt{3}(\sqrt{2}V)\sin\omega t \qquad \text{Eq 8-5}$$

and similarly with an ABC-sequence of voltages

$$V_{AC} = \sqrt{3}(\sqrt{2}V)\sin(\omega t - 60^o) \qquad \text{Eq 8-6}$$

The DC Link voltage is then found by performing a loop analysis on the circuit of Figure 8-3

$$V_d = -L_C\frac{di_{T1}}{dt} + V_{AB} = V_{AB} - 0.5V_{AC} \qquad \text{Eq 8-7}$$

At the end of the commutation period $\omega t = \alpha + u$, $i_{T5} = I_d$ and $i_{T1} = I_d$. Substituting Equation 8-4 into Equation 8-7 and setting the limits of integration results in,

$$I_d = \frac{1}{2\omega L}\int_{\alpha+(\frac{\pi}{3})}^{\alpha+(\frac{\pi}{3})+u} V_{AC}\,d(\omega t) \qquad \text{Eq 8-8}$$

Next, substituting Equation 8-6 into Equation 8-8, performing the integration and simplifying results in

$$\cos\alpha - \cos(\alpha - u) = \frac{2\omega L_C}{\sqrt{6}V} I_d \qquad \text{Eq 8-9}$$

Figure 8-2 shows the delay angle β which is called the commutation lead angle. It is measured with respect to the instant when V_{AC} becomes negative and is given by [29]

$$\beta = 180^o - \alpha \qquad \text{Eq 8-10}$$

Substituting β into Equation 8-9 yields

$$\cos(\beta - u) - \cos\beta = \frac{2\omega L_C}{\sqrt{6}V} I_d \qquad \text{Eq 8-11}$$

Equation 8-11 relates how u changes for different values of machine excitation voltage (V), link current (I_d), rotor speed (ω), lead angle (β) and commutation inductance (L_c).

The margin angle γ is now defined to be

$$\gamma = \beta - u \qquad \text{Eq 8-12}$$

Figure 8-4 shows the waveforms of the motor terminal voltage and current with the machine power factor angle $\phi = (\beta - 0.5u)$ in a leading condition. Note that the firing angle (or the lead angle) together with the resulting commutation overlap angle will dictate the machine power factor.

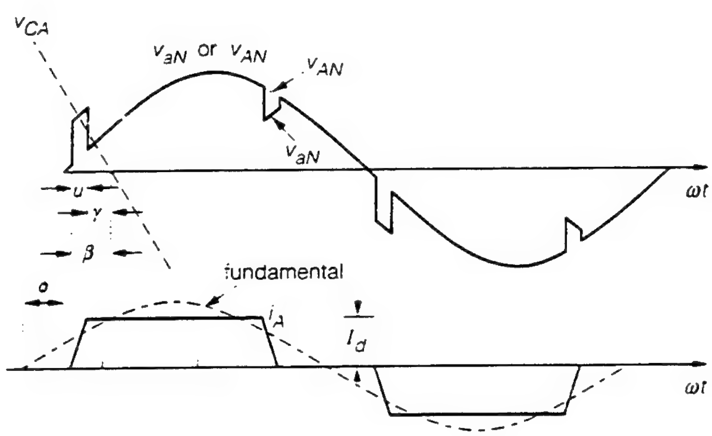

Figure 8-4. Waveforms of the motor terminal voltage and current with the machine power factor angle ϕ [30].

For a six-step current waveform (Figure 8-4) and neglecting the commutation overlap, the fundamental RMS current and the total RMS current are given by

$$I_S = \frac{\sqrt{6}}{\pi} I_d \qquad \text{Eq 8-13}$$

$$I_{RMS} = \sqrt{\frac{2}{3}} I_d \qquad \text{Eq 8-14}$$

A phase shift of $0.5u$ in the stator's current is caused by commutation overlap. The magnitude of I_S remains constant.

Assuming zero commutation overlap, the average value of V_d is

$$V_d = \frac{3}{\pi} \int_{\alpha+(\frac{\pi}{3})}^{\alpha+(\frac{2\pi}{3})} V_{AB} d(\omega t) = \frac{3\sqrt{6}}{\pi} V \cos\alpha \qquad \text{Eq 8-15}$$

The effect of commutation overlap is incorporated into V_d by noting that V_{AB} must be modified to $V_{AB} - 0.5V_{AC}$ as shown in Equation 8-7 so that

$$V_d = \frac{3\sqrt{6}V}{\pi} \cos\alpha - \frac{3}{\pi} \omega L_c I_d \qquad \text{Eq 8-16}$$

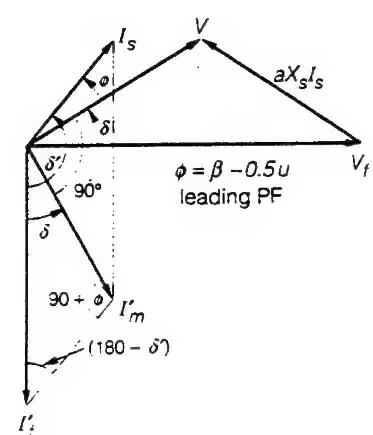

Figure 8-5. Phasor diagram for synchronous motor using load commutation [29].

For α >90° and β < 90° a representative phasor diagram for the motor operating with load commutation is shown in Figure 8-5.

From the results illustrated in Equations 8-1 through 8-16 and given a value for the winding resistance of the stator, R_S, power and torque for the motor can be calculated.

The power input to the motor is

$$P_{in} = -V_d I_d \qquad \text{Eq 8-17}$$

Ignoring core losses, the power developed by the motor is

$$P_{motor} = P_{in} - 3I_{RMS}^2 R_s \qquad \text{Eq 8-18}$$

By substituting Equation 8-14 into 8-18, the power of the motor is expressed by

$$P_{motor} = -V_d I_d - 2I_d^2 R_s \qquad \text{Eq 8-19}$$

The developed torque is given by

$$T = \frac{P_{motor}}{\omega_{motorshaft}} \qquad \text{Eq 8-20}$$

and thus the torque can be adjusted by controlling the DC link current.

Two other equations governing the power from the motor and the developed torque are

$$P_{motor} = 3VI_s \cos\phi - 3I_{RMS}^2 R_s \qquad \text{Eq 8-21}$$

$$T = \frac{3}{\omega_{motorshaft}}[VI_s \cos\phi - I_{RMS}^2 R_s] \qquad \text{Eq 8-22}$$

4. **DC Link Synchroconverter and Synchronous Motor Control Systems Analysis**

The general layout for the control system for the converter and synchronous motor is presented in Figure 8-6. A wound rotor synchronous motor is being used in the system. The speed control of the motor is based on two conditions of operation: below base speed and above base speed. Operation below base speed, is accomplished by controlling the rectifier output voltage of the converter. An increase in the rectifier output voltage with β being fixed will cause an increase in the DC link current, I_d [30]. The increase in DC Link current results in an increase in torque as illustrated in Equation 8-19. With the increase in torque the synchronous motor will accelerate and the induced voltage, V, increases until a balance is achieved between the rectifier output voltage and to the inverter counter EMF, V_d. With the wound-rotor synchronous motor, the field current is also controlled below base speed to maintain a constant flux [30].

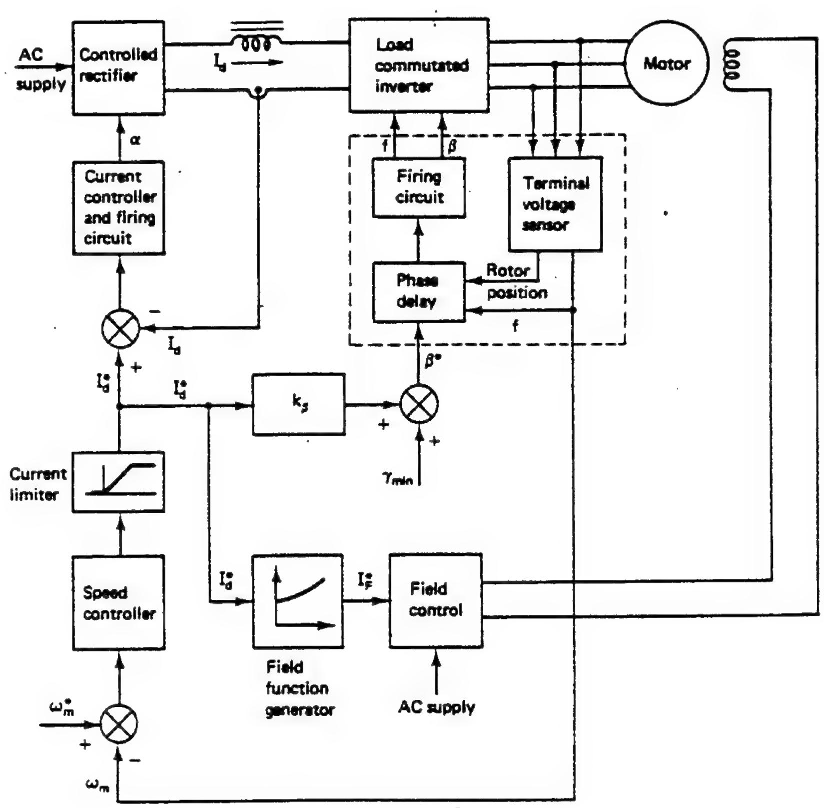

Figure 8-6. Functional diagram for the controls of a current source converter supplying a synchronous motor using constant commutation lead angle control [29].

Speed control is achieved above base speed by adjusting the field current. Higher speeds are obtained by reducing the field current. A reduction in the field current to the rotor reduces the magnetic flux current, I_M. The induced voltage, V, is reduced by the decrease in the magnetic flux current. With a reduction in induced voltage, the inverter counter EMF voltage, V_d, is reduced and I_d and the motor torque increases. The motor speed will continue to increase until V achieves a value at which the rectifier voltage balances the inverter counter EMF, V_d.

There are a number of approaches available for inverter control. The two most commonly found with current source inverters are the constant margin angle control and the constant commutation lead angle. The constant margin angle control operates the inverter at the minimum safe value of the margin angle [31]. Operation with the minimum safe value of the margin angle facilitates the highest power factor and the maximum torque-per-ampere which in turn allows efficient operation of the motor and the inverter. Because it is impossible to always predict the minimum margin angle for all the different operating conditions, an estimation is used with a factor for safety. The estimation controls are both difficult to design and are very complex. For these reasons, the use of a constant margin angle control is limited.

The second approach for inverter control is the constant commutation lead angle. This method is considerably simpler to implement when the inverter operates at a constant β. From the following equation, the value of operating with constant commutation lead angle can be assessed.

$$\beta_{\min} = u + \gamma_{\min} \qquad \text{Eq 8-23}$$

From Equations 8-11 and 8-23,

$$\cos(u + \gamma_{\min}) = \cos\gamma_{\min} - \frac{2\omega L_c I_d}{\sqrt{6}V} \qquad \text{Eq 8-24}$$

From Equations 8-23 and 8-24, Equation 8-25 is developed where K is a constant introduced to provide a margin of safety.

$$\cos\beta_{\min} = \cos\gamma_{\min} - K(\frac{I_d}{I_m}) \qquad \text{Eq 8-25}$$

From Equation 8-24, the highest value of β_{min} is when I_d/I_m has the highest value. When operating at base speed, the value of I_d/I_m has the highest value when I_d is at a maximum. From Equations 8-19 and 8-20 when I_d is maximum, the torque is also at a maximum. When the inverter is operated at a constant β, which is the minimum at the maximum value of I_d, then commutation is always ensured for all operating points [30]. At maximum torque the motor will operate at the highest power factor. However, at low torque values the power factor and efficiency will be lower due to a decrease in u, the commutation over-lap angle. When the machine also operates above base speed at a constant voltage, the minimum value of β is at its maximum when the motor operates at maximum I_d and the highest speed. This can be verified by solving Equations 8-23 and 8-24 for different values of I_d and ω [30]. The minimum value of β is normally chosen based on the point of maximum I_d and ω. The drawback to this design is that at lower values of speed and DC link current the efficiency and power factor are low compared to the constant margin angle control.

5. DC Link Synchroconverter and Synchronous Motor Operational Issues

There are several issues that need to be addressed in the operation of a DC link synchroconverter and synchronous motor using load commutation. Difficulties are encountered in starting the synchronous motor using the self-control method of operation. The motor's induced voltages are too small to provide satisfactory performance in turning the electronic devices off. To start the motor, a pulse method of operation is employed. The basic principle of pulse operation is to disable the self-control system, have the rectifier produce the largest I_d available and use a oscillator at a predetermined setting to fire the electronic devices. Once the motor is up to 10% of the base speed the self control system using constant commutation lead angle strategy would take over [29].

At very low speeds the motor is running at both a lower power factor and a low efficiency. It would be advantageous to operate the motor closer to its highest speed the majority of the time. In Chapter VII the operation of a controllable-pitch screw propeller was introduced for use with an electric propulsion system. If load commutation is employed, the use of a controllable-pitch propeller would be the best alternative in the total system design. First, the need to stop and restart the motor for changes in direction would be eliminated for normal operating conditions, reducing the use of the pulse method of control. Second, the motor could be allowed to rotate at a set rpm even when the ship is at zero speed. This would allow a higher efficiency and power factor compared to a speed range starting at zero.

As previously discussed in Chapter V, harmonics are a concern to the electric propulsion system. At low speeds harmonics distort the machine terminal voltages, increase losses and produce torque pulsations which cause stepped motion. The following Fourier series expansion of the phase current waveform illustrates the rich harmonic spectrum.

$$I_{AS} = \frac{2\sqrt{3}}{\pi} I_d [\cos\omega_e t - \frac{1}{5}\cos 5\omega_e t + \frac{1}{7}\cos 7\omega_e t - \frac{1}{11}\cos 11\omega_e t.+\ldots] \qquad \text{Eq 8-26}$$

where $I_{AS,pk} = I_d$

$$I_{AS,RMS} = \sqrt{\frac{2}{3} I_d}$$

and the peak of the fundamental is $I_{AS,pk} = \dfrac{2\sqrt{3}}{\pi} I_d$

For an inverter using load commutation, damper windings are beneficial in reducing the distortion of the machine terminal voltage. In addition, the damper windings offer a low impedance path to the harmonic currents previously discussed making the magnetizing current and flux nearly sinusoidal and in turn making the terminal voltage nearly sinusoidal [30]. The damper windings also reduce the commutating inductance which helps reduce the commutation overlap. Due to the numerous advantages accrued by using damper windings, they are always used in self-controlled synchronous motor drives

utilizing load commutation. When using self-controlled synchronous motor drives utilizing line commutation with a cyclcoconverter, the motor is not fitted with damper windings. The damper windings have the effect of reducing the leakage inductance and in turn reducing the filtering of the applied voltages.

IX. ANALYSIS OF A SIX-PHASE SYNCHRONOUS MACHINE

A. SIX-PHASE SYNCHRONOUS MACHINE DESIGNS AND MACHINE EQUATIONS

1. Advantages of Six-Phase Machines

In Chapter V the types of converters and motors available for electric propulsion were introduced. The induction and synchronous motors are currently the only available choices for electric propulsion. Based on the types of converters available and the representative control systems introduced in Chapter VIII, it appears that the synchronous motor is the most acceptable choice for electric propulsion. This is further evidenced by the fact that synchronous motors are widely used in the commercial merchant fleet electric propulsion systems[4].

In Chapter V several different topologies were introduced using either a six-phase synchronous motor or two three-phase synchronous motors. Both systems provide enhanced redundancy for the propulsion system and minimize the effects of harmonics from both two six-phase converters or from a single 12-pulse configuration. A single six-phase motor typically yields a more compact design as compared to mounting two machines on the same shaft.

2. Design of the Six-Phase Synchronous Motor

The synchronous propulsion motor will have to meet the requirements associated with the design of the propulsion system. This primarily applies to matching the motor design to the propulsion system type of converter. For example, from Chapter V the use of a 12-pulse synchroconverter requires that the two three-phase winding sets be offset by 30°. A 12-pulse cycloconverter does not require a six-phase motor for operation. In the case of two six-pulse cycloconverters, the windings of each phase are equally spaced around the stator. Another issue with the design of the motor is the possibility of a failure of one winding causing damage to another winding rendering the motor inoperable. In this case the construction of the motor can enhance survivability. Other issues concerning the motor design and type of converter employed include: the use of damper windings, the methods used to reduce the effects of harmonics on the motor and number of poles for the machine.

Even though the motor must match the operating characteristics of the converter, there are additional design issues to be considered including the air gap size, type of cooling, voltage and current ratings, and building materials.

The following section details the dynamic equations required to model a six-phase synchronous machine where the stator winding sets are displaced by 30°. These equations can be combined into a larger system simulation to access the performance of the propulsion system and aid in the design of the converter control system. Such an endeavor is an excellent extension of the work provided thus far.

3. Modeling Equations for Six-Phase Synchronous Motor

The six-phase machine is most conveniently represented and analyzed in the rotor reference frame. The transformation may be viewed as replacing the individual stator winding sets by fictitious sets fixed on the rotor. By constraining all windings to the rotor, the winding inductances become constants. The substantial benefit comes at the minimal cost of introducing speed voltage terms in the stator voltage equations[31]. The transformations into the rotor reference frame in matrix form are given by

$$\begin{bmatrix} E^r_{qs1} \\ E^r_{ds1} \\ E_{os1} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta_r & \cos\left(\theta_r - \frac{2\pi}{3}\right) & \cos\left(\theta_r + \frac{2\pi}{3}\right) \\ \sin\theta_r & \sin\left(\theta_r - \frac{2\pi}{3}\right) & \sin\left(\theta_r + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} E_{as1} \\ E_{bs1} \\ E_{cs1} \end{bmatrix} \qquad \text{Eq 9-1}$$

$$\begin{bmatrix} E^r_{qs2} \\ E^r_{ds2} \\ E_{os2} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\left(\theta_r - \frac{\pi}{6}\right) & \cos\left(\theta_r - \frac{5\pi}{6}\right) & \cos\left(\theta_r + \frac{\pi}{2}\right) \\ \sin\left(\theta_r - \frac{\pi}{6}\right) & \sin\left(\theta_r - \frac{5\pi}{6}\right) & \sin\left(\theta_r + \frac{\pi}{2}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} E_{as2} \\ E_{bs2} \\ E_{cs2} \end{bmatrix} \qquad \text{Eq 9-2}$$

where the E may be current, voltage or flux linkage. The angle θ_r is the rotor electrical angle and is found by integrating the rotor electrical angular velocity. The difference in angles between the two

transformation results are due to the windings being displaced by 30°. The inverse transformations are given by

$$\begin{bmatrix} E_{as1} \\ E_{bs1} \\ E_{cs1} \end{bmatrix} = \begin{bmatrix} \cos\theta_r & \sin\theta_r & 1 \\ \cos\left(\theta_r - \frac{2\pi}{3}\right) & \sin\left(\theta_r - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta_r + \frac{2\pi}{3}\right) & \sin\left(\theta_r + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} E^r_{qs1} \\ E^r_{ds1} \\ E_{os1} \end{bmatrix} \quad \text{Eq 9-3}$$

$$\begin{bmatrix} E_{as2} \\ E_{bs2} \\ E_{cs2} \end{bmatrix} = \begin{bmatrix} \cos\left(\theta_r - \frac{\pi}{6}\right) & \sin\left(\theta_r - \frac{\pi}{6}\right) & 1 \\ \cos\left(\theta_r - \frac{5\pi}{6}\right) & \sin\left(\theta_r - \frac{5\pi}{6}\right) & 1 \\ \cos\left(\theta_r + \frac{\pi}{2}\right) & \sin\left(\theta_r + \frac{\pi}{2}\right) & 1 \end{bmatrix} \begin{bmatrix} E^r_{qs2} \\ E^r_{ds2} \\ E_{os2} \end{bmatrix} \quad \text{Eq 9-4}$$

The synchronous motor under consideration has a rotor equipped with a field winding (*fd*) and two short-circuited damper windings (*kq* and *kd*). The field winding is supplied a DC voltage from a slip ring assembly or a brushless excitation system. The field winding has a resistance r_{fd} and the damper windings have resistances r_{kq} and r_{kd}, respectively. The stator windings are identical and sinusoidally-distributed with resistance r_s. It is common to represent the dynamic response of a motor by a set of nonlinear differential equations[31]. The equations are derived from the analysis of linear magnetic circuits and then the application of transformation theory.

To facilitate the transformation and the realization of convenient circuit representations, the rotor windings are replaced by windings having the same number of turns as the stator windings. This results in the introduction of primed or referred quantities. The equations are then transferred to the rotor reference frame. The superscript "r" represents stator variables which are transferred to the rotor reference frame.

Upon applying these transformations to the stator voltage equations, the following results[32]

$$\begin{bmatrix} v_{qs1}^r \\ v_{ds1}^r \\ v_{qs2}^r \\ v_{ds2}^r \end{bmatrix} = \begin{bmatrix} r_s & 0 & 0 & 0 \\ 0 & r_s & 0 & 0 \\ 0 & 0 & r_s & 0 \\ 0 & 0 & 0 & r_s \end{bmatrix} \begin{bmatrix} i_{qs1}^r \\ i_{ds1}^r \\ i_{qs2}^r \\ i_{ds2}^r \end{bmatrix} + \begin{bmatrix} \frac{\rho}{\omega_b} & \frac{\omega_r}{\omega_b} & 0 & 0 \\ -\frac{\omega_r}{\omega_b} & \frac{\rho}{\omega_b} & 0 & 0 \\ 0 & 0 & \frac{\rho}{\omega_b} & \frac{\omega_r}{\omega_b} \\ 0 & 0 & -\frac{\omega_r}{\omega_b} & \frac{\rho}{\omega_b} \end{bmatrix} \begin{bmatrix} \psi_{qs1}^r \\ \psi_{ds1}^r \\ \psi_{qs2}^r \\ \psi_{ds2}^r \end{bmatrix} \qquad \text{Eq 9-5}$$

$$\begin{bmatrix} 0 \\ 0 \\ \upsilon_{fd}' \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ e_x \left\langle \frac{r_{fd}'}{X_{md}} \right\rangle \end{bmatrix} = \begin{bmatrix} r_{kq}' & 0 & 0 \\ 0 & r_{kd}' & 0 \\ 0 & 0 & r_{fd}' \end{bmatrix} \begin{bmatrix} i_{kq}' \\ i_{kd}' \\ i_{fd}' \end{bmatrix} + \frac{\rho}{\omega_b} \begin{bmatrix} \psi_{kq}' \\ \psi_{kd}' \\ \psi_{fd}' \end{bmatrix} \qquad \text{Eq 9-6}$$

where ρ is the $\frac{d}{dt}$ operator, ψ is flux linkages per second, ω_b is the base electrical angular machine speed and ω_r is related to the actual rotor speed in rad/sec by

$$\omega_r = \frac{P}{2}\omega_{rm} \qquad \text{Eq 9-7}$$

The flux linkage per second are related to the currents by

$$\begin{bmatrix} \psi_{qs1}^r \\ \psi_{ds1}^r \\ \psi_{qs2}^r \\ \psi_{ds2}^r \end{bmatrix} = \begin{bmatrix} X_{q1} & 0 & X_{q2} & 0 \\ 0 & X_{d1} & 0 & X_{d2} \\ X_{q2} & 0 & X_{q1} & 0 \\ 0 & X_{d2} & 0 & X_{d1} \end{bmatrix} \begin{bmatrix} i_{qs1}^r \\ i_{ds1}^r \\ i_{qs2}^r \\ i_{ds2}^r \end{bmatrix} + \begin{bmatrix} X_{mq} & 0 & 0 \\ 0 & X_{md} & X_{md} \\ X_{mq} & 0 & 0 \\ 0 & X_{md} & X_{md} \end{bmatrix} \begin{bmatrix} i_{kq1}' \\ i_{kd}' \\ i_{fd}' \end{bmatrix} \qquad \text{Eq 9-8}$$

$$\begin{bmatrix} \psi_{kq1}' \\ \psi_{kd}' \\ \psi_{fd}' \end{bmatrix} = \begin{bmatrix} X_{mq} & 0 & X_{mq} & \\ 0 & X_{md} & 0 & X_{md} \\ 0 & X_{md} & 0 & X_{md} \end{bmatrix} \begin{bmatrix} i_{qs1}^r \\ i_{ds1}^r \\ i_{qs2}^r \\ i_{ds2}^r \end{bmatrix} + \begin{bmatrix} X_{kq}' & 0 & 0 \\ 0 & X_{kd}' & X_{md} \\ 0 & X_{md} & X_{fd}' \end{bmatrix} \begin{bmatrix} i_{kq1}' \\ i_{kd}' \\ i_{fd}' \end{bmatrix} \qquad \text{Eq 9-9}$$

where the reactances listed are written in terms of the machine reactances as

$$X_{d1} = X_{lsd} + X_{lmd} + X_{md} \qquad \text{Eq 9-10}$$

$$X_{d2} = X_{lmd} + X_{md} \qquad \text{Eq 9-11}$$

$$X_{q1} = X_{lsq} + X_{lmq} + X_{mq} \qquad \text{Eq 9-12}$$

$$X_{q2} = X_{lmq} + X_{mq} \qquad \text{Eq 9-13}$$

$$X'_{kq} = X_{mq} + X'_{lkq} \qquad \text{Eq 9-14}$$

$$X_{d2} = X_{lmd} + X_{md} \qquad \text{Eq 9-15}$$

$$X_{q1} = X_{lsq} + X_{lmq} + X_{mq} \qquad \text{Eq 9-16}$$

$$X_{q2} = X_{lmq} + X_{mq} \qquad \text{Eq 9-17}$$

$$X'_{kq} = X_{mq} + X'_{lkq} \qquad \text{Eq 9-18}$$

$$X'_{kd} = X_{md} + X'_{lkd} \qquad \text{Eq 9-19}$$

$$X'_{fd} = X_{md} + X'_{lfd} \qquad \text{Eq 9-20}$$

Finally, the torque expression in terms of transformed variables is given by

$$T_e = \frac{3P}{4\omega_b}\left(\psi^r_{ds1} i^r_{qs1} - \psi^r_{qs1} i^r_{ds1}\right) + \frac{3P}{4\omega_b}\left(\psi^r_{ds2} i^r_{qs2} - \psi^r_{qs2} i^r_{ds2}\right) \qquad \text{Eq 9-21}$$

From the equations above and information provided from the motor and electric propulsion system, the Advanced Continuous Simulation Language (ACSL) can be used to model the six-phase motor. It is also possible to model both the converter and motor together to reveal simulated operation of an electric propulsion system. This is an excellent research topic for a future thesis project.

X: SURFACE COMBATANT INTEGRATED ELECRTIC SYSTEM DESIGN

This chapter contains the components for an electric propulsion system utilizing an Integrated Electrical System (IES). It is not intended to be a detailed design nor is it proposed to be an optimal design. It simply represents one intelligent way to realize an IES. The components of the design are based on the components that were presented in the previous chapters. The components that are utilized are within current design capability. Some components may already be available. The architecture for the electric propulsion and an IES are orientated to achieve maximum use of their advantages.

A. REQUIREMENTS AND DESIGN FOR THE INTEGRATED ELECTRICAL SYSTEM

To effectively design the best IES, the system requirements must be adequately defined. The system is analyzed through a set of measures of effectiveness and then will be considered for an overall measure of performance.

1. Requirements for a Model Electric Propulsion and the IES

The following nominal requirements are assumed. A frigate-sized warship is considered (500ft long, 4,500 tons displacement) yielding requirements comparable to the U. S. Navy's Oliver Hazard Perry class. For propulsion the ship will require 45,000HP and the capacity to achieve a top speed of 30 knots and a speed of 20 knots for operation on half the total horsepower. In an effort to maintain redundancy while keeping required space at a minimum, the vessel will have a minimum of two and a maximum of four prime movers for ship's propulsion. The vessel is assumed to be equipped with two 750HP maneuvering thrusters capable of a speed of 5 knots. Unlike the U. S. Navy's Oliver Hazard Perry class, the APU will be powered from the IES and not from the ship's service electrical system. The maneuvering thrusters will be included in the total power required from the ship's prime movers.

The ship's service electrical load requires 1,800kW for normal operation underway and 2,500kW during battle conditions. While in port the ship's service electrical load requires 1,000kW. The ship's service electrical system will be supplied from the IES and a minimum of two and a maximum of four

ship's service generators will be installed. Each ship's service generator is able to supply the entire ship's service electrical load for normal operation underway. The ship's electric propulsion and the IES are designed to support Pulse-Energy Weapons (PEW) when they become available.

B. THE NUMBER, TYPES AND RATINGS OF COMPONENTS

1. Prime Movers

For the model electric propulsion and the IES, the following table lists the number, type and ratings of the prime movers for the ship.

	Propulsion Prime Mover	Ship's Service Prime Mover
Type of Prime Mover	LM2500 Marine Gas turbine	Allison 501K Gas Turbine
Rating in Horsepower (MW)	25,000 (18.65)	2,680 (2.0)
Speed in RPM	3,600	3,600
Number	2	2
Total Power Horsepower (MW)	50,000 (37.3)	5,360 (4.0)

Table 10-1. Type, number and ratings of the prime movers.

For any size vessel, efficiency, manning, weight and size make the use of conventional or nuclear steam prime movers prohibitive. Due to size limitation inside the hull, utilizing gas turbines provide greater power per volume than diesel engines. As previously established the standard gas turbine used for main propulsion in the U. S. Navy today is the General Electric LM2500. For his reason the LM2500 was selected to be the prime mover in the model system. Three major classes of ship have gas turbine prime movers for use with ship's service generators. The gas turbine that is used is the Allison 501K. Because the Allison 501K is already being used, its reliability and maintenance support are already in place. It is understood that a different type of ship may yield a different result in terms of types and numbers of prime movers.

2. Generators

For the model electric propulsion and the IES, the following table lists the number, type and ratings of the generators for the ship.

	Main Propulsion Generator	Ship's Service Generator
Speed in RPM	3,600	3,600
Rated Voltage in kV	6.6	6.6
Number of Poles	4	4
Number of Phases	3	3
Frequency in Hz	120	120
Rated Power in MW	18	1.9
Rated Power Factor Percentage	.90	.90
Electrical Efficiency	98%	98%
Class of Insulation	C	C
Stator cooling	Air Cooled/with seawater exchanger	Air Cooled/with seawater exchanger

Table 10-2. Ratings of the propulsion and ship's service generators.

For the proposed system all generators will operate at the same voltage and frequency. This enables all generators to provide power to common users without needing to alter the output of the generator. As specified in Chapter I, the following relationship dictates the required speed and pole number for each generator assuming a 120Hz output is requested.

$$f = \frac{n*N}{120} = \frac{3600*4}{120} = 120Hz \qquad \text{Eq 10-1}$$

A voltage rating of 6.6kV is the value currently being used on board cruise ships and ice breakers, thus the components to support this voltage level are readily available [24,11]. This voltage level is considered by makers of electric propulsion systems to be optimal with existing power electronic devices

and equipment [11]. The use of a higher voltage would decrease the size of the transmission systems and components, but would cause a considerable increase in the size of step down transformers. The frequency of 120Hz is based on three issues. First, the addition of two poles to a current 60Hz generator operating at 3,600 rpm is all that is required to change the frequency to 120Hz. It should be noted that most generators under production operate at 60 or 50 Hz. Other methods of changing frequency would require altering the prime mover's speed or adding gears for a speed increase of the generator. These methods reduce the efficiency of the prime mover and make use of gears which were not intended to be used with electric propulsion and the IES. Another method is to increase the number of poles to achieve frequencies greater than 120Hz. The use of higher frequencies effect the design, construction and operation of the generator. Operation with 60Hz is an alternative that is currently being used on other ships employing electric propulsion. The advantage to using higher frequencies, as noted in Chapters V, VI and VII, are reduced size and weight of generators, transformers and converters. Additionally, harmonics are reduced throughout the propulsion and ship's service systems.

3. Main Propulsion Frequency Converters

The type of converter to be used is a cycloconverter.

Number of Converters	2
Voltage per Phase in kV	1.4
Power in MW	16.5
Number of Pulses	12
Transformer Rating per Phase kV	6.6/1.5
Method of Cooling	Liquid

Table 10-3. The number, rating and design of the frequency converter.

As presented in Chapter V, the cycloconverter is one of the two types of frequency converters currently used with electric propulsion. The cycloconverter operates at a lower voltage than the power supply to enable the use of smaller voltage electronic devices. The reason for the use of the cycloconverter

is the reduced harmonics. The reduction of harmonics is further enhanced by the use of 12-pulse rectifiers within the cycloconverter. However, the use of a 12-pulse topology requires transformers. These transformers accomplish phase shifting, serve as a commutating reactance and facilitate a reduction in power distortion along with voltage reduction. A discussion of the 12-pulse cycloconverter was detailed in Chapter V and additional information is found in [33].

4. Propulsion Motor

The electric propulsion motor to be used is a field-wound salient-pole synchronous motor. The field excitation is provided to the rotor either by slip rings and brushes or a brushless excitation system.

Number of Motors	2
Type of Coupling to Propeller	Direct Couple
Voltage in kV	3.2
Power in MW	18.0
Number of Phases	6 (2 sets of three)
Number of Poles	32
Rpm's	180
Cooling	Liquid Cooled

Table 10-4. Number, rating and design features of the cycloconverter.

The synchronous motor is double-wound to facilitate the 12-pulse cycloconverter and to provide redundant operation of the motor. The synchronous motor will have two sets of windings decoupled magnetically so that their voltages do not produce high interacting current harmonics [14]. The synchronous motor will not be fitted with a damper winding when using cycloconverters. The motors will drive a controllable-pitch propeller. From the information on propellers described in Chapter VII, the best choice is the controllable pitch design.

5. The Ship's Service Electrical System

The ship's service electrical system will be a DC ZEDS architecture. The DC ZEDS is still under development. The parameters of the final system to be implemented are still under consideration. The values given are the estimated values from developmental work [19].

The system will have four rectifiers to supply the two DC buses, with any two being able to carry the entire ship's service load. The rectifiers will be fed from the main bus. The two DC buses will operate at 1,800 volts and 2,000Amps. Each bus will feed each of the electrical zones of the ship. From the buses, SSCMs and SSIMs will convert the DC power to different DC voltage levels and to AC power as required. A detailed layout and operation was presented in Chapter VI.

6. Maneuvering Thrusters

The maneuvering thrusters for the ship will use PWM VSI converters feeding induction motors. The PWM converters and induction motors will be one unit. The PWM will be able to start and operate the motors for the maneuvering thrusters with minimum effect on the main bus. The maneuvering thruster operation is described in Chapter VI.

7. Pulse-Energy Weapon Configuration

The PEW system will be provided power from either of the two main propulsion generator via diverter switches. The system will use a converter to increase the supply frequency prior to the step up transformer and rectifier. The ship will be fitted with only one frequency converter for the PEW that can be supplied from either propulsion generator.

XI. CONCLUSION

The concepts of electric propulsion and the Integrated Electrical System (IES) are being developed for the surface combatant of the 21st Century. The U. S. Navy is actively engaged in the development of cost-effective platforms that enhance operational flexibility, maximize survivability, decrease manning, improve producibility and decrease overall cost. On-going research efforts in power electronics, electro-mechanical machinery and the DC Zonal Electric Distribution System (DC ZEDS) reflect the push towards using mature high-technology together with improved total ship system design in the future surface combatant. In particular, this thesis contains a synopsis of the current state of the technology available, enumerates the possible topologies, contains a discussion of the advantages and disadvantages of each, lists a description of the operation and control of one candidate electric propulsion system, sets forth modeling equations for use in future efforts and characterizes a representative system design.

A. INTEGRATED ELECTRICAL SYSTEM ANALSIS RESULTS

An example of high-technology impacting future ship design is the concept of an IES, the focus of this research effort. Within the framework of this analysis, it was found that an IES offers several marked advantages over current ship design. Since both ship service and ship propulsion requirements are derived from common prime movers and generators, several dedicated ship service electrical system prime movers and generators can be eliminated. In addition to the cost savings, substantial reductions in manning and improved reliability are realized with the IES. Increasing the loading on the propulsion prime mover nearer to the rated level also results in more efficient operation. An IES also provides what is called cross-connect capability where any prime mover can power any propulsion frequency converter which can drive any of the propulsion motors and propellers. This introduces a degree of flexibility and reliability unmatched by the direct drive counterpart. In addition, by decoupling the prime mover speed from the speed of the propeller, the prime mover can be operated at a more efficient speed, resulting in significant gains in fuel efficiency and emissions control. An IES also facilitates vertical integration where the shaft, power transmission components and prime movers are no longer required to be in line with one another.

As explained in this thesis, this enables engineering spaces to be redesigned and optimally used while eliminating the requirement of aligning propulsion components across several watertight compartments. With a clutch or reduction gear no longer needed, it is well known that electric propulsion offers superior acoustic performance which is important in minimizing the signature of a surface combatant. An electric propulsion system also makes speed control and ship reversal simple and rapid. Finally, the electrical capacity now readily available on board ship can be used to power auxiliary systems under development such as Electro-Magnetic Aircraft Launching Systems (EMALS) and Pulse-Energy Weapons (PEW).

The advantages of an IES listed above are being utilized in ships such as icebreakers, research vessels, oil tankers and passenger liners. Applications in surface combatants have up to now been stymied by the volume and weight of existing technology. In particular, the power density of an electric propulsion system is less than the mechanical counterpart, resulting in large spaces being required for the electro-mechanical machinery and converters. Thus, despite offering the advantage of vertical integration, current electric propulsion systems actually require more space. Therefore, much of the gains in space accrued from improved fuel efficiency are sacrificed to components of the electric propulsion system. Machinery and power electronic technology, however, are developing a number of devices that may mitigate this disadvantage. As described previously, permanent magnet, transverse flux and superconducting machines offer exciting possibilities for markedly increasing the power density of electric propulsion. An additional disadvantage of electric propulsion is the harmonics produced by the propulsion frequency converters. These harmonics are now available to potentially corrupt the distribution system. In this area, clear tradeoffs in size, complexity and cost exist in addressing the problem as detailed in this thesis.

B. ANALYSIS OF COMPONENTS

An IES contains prime movers, generators, propulsion frequency converters, propulsion motors, propellers and a distribution architecture including any attendant power converters. This thesis has identified the principle devices under consideration in each area and has set forth the basic operational characteristics, advantages and disadvantages. The consideration of the compatibility of the various components is an ambitious multi-disciplinary endeavor which required an extensive literature search and much back ground reading to uncover all of the relevant issues. In particular, the choice of propulsion

much back ground reading to uncover all of the relevant issues. In particular, the choice of propulsion motor and converter yielded many options with the most likely candidates, using existing technology, being the field-wound synchronous motor employing either a cycloconverter or a synchroconverter. Additional machine winding sets require more complicated converters but offer advantages in terms of harmonics, redundancy, and in some cases, machine design. This thesis has attempted to outline the pertinent issues associated with each component and focus subsequent researchers onto key design tradeoffs.

Additional examples include tradeoffs between prime movers, ship's service electrical distribution architectures, and propeller types. This thesis is certainly not a definitive exposition on any of these components but serves as a primer on the interconnection and interrelationships of these devices for a surface combatant application. For instance, this thesis addressed why a controllable-pitch propeller would be attractive despite the cavitation issues introduced. Another example of the analysis contained in this thesis is the comparison between the harmonic produced by a cycloconverter and the harmonics produced by a synchroconverter when used with electric propulsion.

C. FUTURE WORK

There are a number of areas ripe for further study. Most important is the evolution of new electro-mechanical machine and frequency converter designs to optimize the size of the electric propulsion system. In addition, to aid in the study of harmonics and the design of feedback control systems, various simulation models are needed which accurately predict the dynamic performance of the various components. Such an undertaking was initiated in this work as illustrated in Chapters VIII and IX. Follow on work could include simulating the prime mover, a generator, a propulsion frequency converter, a propulsion motor and the propeller dynamics to illustrate various operational maneuvers and to predict various system waveforms. Such simulations efforts could uncover important information regarding the design and operation of individual components.

An IES is in the future for the U. S. Navy. The advantages are too persuasive to ignore and the technology is progressing to rapidly to dismiss. As evidenced by research being conducted around the

globe, the IES will happen soon. This thesis has sought to organize the baseline information required for subsequent studies at the Naval Postgraduate School.

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